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PROPAGATION MODELING AND ANALYSIS FOR HIGH ENERGY
LASERS

Science Applications,
Incorporated

Prepared for:

Naval Surface Weapons Center

April 1975

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This report analyzes simplified propagation codes and recommends improved models for characterizing the propagation of high energy CW laser beams.

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PROPAGATION MODELING AND ANALYSIS
FOR HIGH ENERGY LASERS

FINAL REPORT

SAI-74-629-WA

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FOREWORD

This is the final report covering work performed
for the Naval Surface Weapons Center under contract
N60921-75-C-0007. The purpose of the contract was to
analyze simplified propagation codes and recommend
improved models for characterizing the propagation of high
energy CW laser beams. The work was performed under the
direction of Mr. Larry Jobson of NSWC.

This report documents the work performed during
the period January-March 1975. It also provides a review
of the earlier work (July 1974-January 1975). The earlier
work was described in detail in interim reports SAI-74-587-
WA (October 1974) and SAI-74-622-WA (January 1975).

The authors wish to express their appreciation to
Dr. Tom Tuer of the SAI Ann Arbor office for his develop-
ment of the multi-line absorption coefficients. We also
thank Mrs. T. Peckham for implementing the numerous code
modifications.

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Section 1

INTRODUCTION

In support of the Systems Analysis Team of the
Naval Surface Weapons Center, Science Applications, Inc.
(SAI), performed a series of tasks designed to develop
a better understanding of the modeling alternatives
available to laser systems analysts and to assist in the
continual improvement of the NGL Engagement Code (NOLEC).
Emphasis was placed on the resolution of propagation
issues of interest to systems analysts. The tasks
involved quantitative comparison of simplified HEL
propagation codes used by DOD analysts, clarification of
the beam quality problem, development of beam distortion
and displacement models, development of a simplified
optical train model, and expansion and improvement of
the AFWL COMBO code.

The work was divided into six tasks. The first
four tasks are reviewed in this report (Section 4), but
are covered more extensively in interim reports (References
1 and 2):

> First Interim Report - July-September 1974,
> SAI-74-587-WA, October 1974 (Reference 1)
> Task 1. Quantitative Comparison of
> Simplified Propagation Codes
>
> Task 3. Beam Quality Modeling.
>
> Second Interim Report - September 1975-
> January 1975, SAI-74-622-WA, January 1975
> (Reference 2)
> Task 2. Beam Shape and Displacement
> Due to Thermal Lensing.
>
> Task 4. Effect of Truncation and
> Obscuration on the Far-Field Beam Profile.

Task 5 required the development of a simplified optical train model. This work is described in Section 2 of this report. Task 6 involved modification and extension of the AFWL CONDO code and included the incorporation of models developed in the earlier tasks. The new version of the code was named SAICON. Section 3 describes the modifications and provides a user's guide to SAICON.

Section 2

A SIMPLIFIED OPTICAL TRAIN MODEL

When performing laser application studies, the
system analyst all too frequently assumes that the
characteristics of the beam leaving the transmitting
optic are the same as the characteristics of the beam
leaving the laser device without regard for any changes
induced by the optical elements and/or components required
to get the beam from the laser device to the transmitting
optic, i.e., the optical train. It is known, however,
that significant changes to the characteristics of the
beam do occur as it propagates through the optical train
(see for example References 3 and 4). The finite absorp-
tivity of the high power mirrors, clipping and blockage
of a portion of the high power beam, and diffraction
effects all reduce the available power in the beam at the
transmitting optic. In addition the optical quality of
the beam is affected by nearly every component or element
through changes in the phase and amplitude distribution of
the beam. Therefore, if realistic estimates of the per-
formance of candidate laser systems are to be obtained
during these application studies, it is important to include
the effect of the optical train on the characteristics of
the laser beam.

An accurate assessment of the impact of the optical
train is a tedious and difficult calculation requiring a
wave optics approach and sophisticated analytical tools for
modeling each of the elements in the optical train. Obviously
these are not very practical for use in systems analysis

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application studies in which a large parameter space must
be investigated. Therefore, if the effect of the optical
train is to be included in such analyses, the development
of simple but reasonably accurate models is required.

One such model has been developed by the AFWL
(Reference 5) which is used in their simplified propagation
code (COMBO). However, its use is somewhat restrictive in
that most of the component effects are left for the user
to specify. Prescriptions for scaling these effects in
terms of system parameters are not given. In addition, the
impact of the optical train on the beam quality is assessed
in terms of peak intensity reduction. Based on work under
this contract, it is felt that an assessment in terms of
the far-field power distribution provides a better charac-
terization of the beam quality (see Reference 1 and Sec-
tion 4.3 of this report).

We have developed a more comprehensive "simplified"
optical train model which can be used to estimate the
degradation in system performance caused by the optical
components required to direct the beam from the laser
device to the transmitting optic (i.e., aerodynamic window,
mirrors, beam expander, etc.). The intent of the model is
not to provide detailed engineering design data but rather
to provide the systems analyst with a rapid assessment
capability which will allow him to perform more realistic
systems analyses of candidate HEL systems. Hence, emphasis
is placed on formulating simple but reasonably accurate
models for the various factors influencing the performance
of the laser system. The approach is similar to that taken
by the AFWL in their simplified model but with new addi-
tions and modifications to make the model more flexible.
The model has been implemented in a subroutine called OPTRAIN
and is included in the SAICOM code as described in Section 3
below.

2.1 MODEL FORMULATION

Conceptually, the optical train may be viewed as a "black box" located between the laser device and the transmitting optic. The input to the box is the output beam from the laser. The model operates on this beam according to the number and type of elements in the train, and its output, in the form of certain performance parameters, provides the input to an atmospheric propagation model. The performance parameters are: (1) the power available at the transmitting optic, (2) beam quality, (3) beam divergence, and (4) beam jitter. In addition, the actual diameter of the beam at the exit aperture is computed for use in the propagation model.

The essential features of the model are illustrated in Figure 2.1. The optical elements and components include (1) an aerodynamic window, (2) a beam clipper, (3) several high power mirrors, (4) a beam expander, (5) an exit aperture, and (6) a focusing element for transmitting the beam to the target plane. In most practical cases the beam expander and focusing element are combined into a single telescope. However, it is convenient for the present analysis to separate them into an ideal beam expander which simply expands the beam and a separate element which applies the curvature to the beam phase front for focusing purposes.

2.1.1 Input Beam

Although it is not an optical element or component, the input beam is necessarily an integral part of the model since it has strong influence on the behavior of the rest of the optical train. In order to simplify the analysis of the components in the optical train, it is assumed that the beam from the laser is circular. However, because of
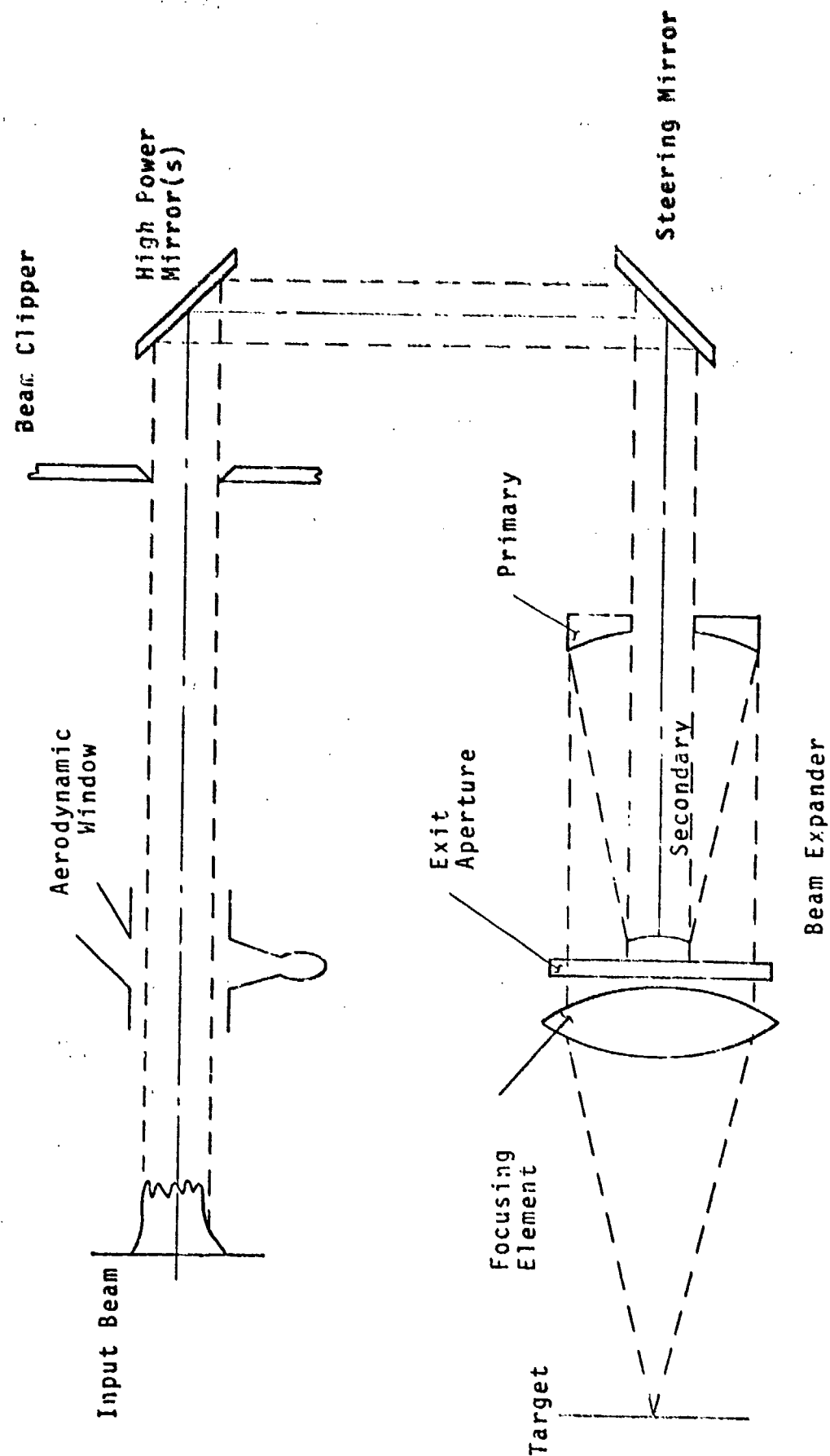
Figure 2.1   Typical Optical Train

the widespread use of unstable resonator configurations to extract power from high power devices, the possibility of a central obscuration in the input beam is incorporated into the model. The inner and outer diameters of the input beam are ϵD_B and D_B respectively. An unobscured input beam profile can be realized by defining $\epsilon = 0$. Other parameters required to specify the input beam are (1) the power in the beam, P_L, (2) the pulse length, Δt, (3) the curvature of the phase front, R_L, and the beam jitter, Θ_L.

In order to evaluate the effect the beam has on the high power mirrors in the optical train, it is also necessary to characterize the intensity profile entering the optical train. This is achieved by specifying both the magnitude and scale size of the intensity fluctuations, the magnitude being specified as a fraction of the average intensity ($\Delta I/I_{ave}$) and the scale size as a fraction of the beam diameter (ℓ_I/D_B). Thus the input beam profile may be visualized as having a uniform intensity I_{ave} with fluctuations ΔI superimposed upon this level.

The optical quality of the input beam is specified by a wavelength scaling factor, n_L. Unfortunately, this definition of beam quality does not allow one to easily incorporate the other beam quality degrading factors induced by the various elements of the optical train. Therefore this parameter is converted by the model into an equivalent root-mean-square phase distortion, σ_L.

Two alternative approaches for this conversion were investigated for use in the model. The first approach is to define the equivalent phase distortion so as to match the reduction in the peak intensity, I_p. According to the analysis presented in Reference 6, the peak intensity reduction is (for a gaussian beam containing small scale random phase variations)

$$I_p/I_g = \exp(-\sigma_L^2)$$

where I_g is the ideal on-axis intensity. According to the wavelength scaling definition of beam quality

$$\frac{I_p}{I_g} = \frac{1}{n_L^2}$$

so that

$$\sigma_L = \sqrt{2\ln(n_L)} . \qquad\qquad (1)$$

It should be noted that this approach is equivalent to the power scaling definition of beam quality and is also the approach taken by the AFWL in their optical system model (Reference 5).

The second approach investigated was to define the equivalent phase distortion to match the power in the "bucket" ($R\lambda/D = 1$) predicted by wavelength scaling. This is given by (Reference 1):

$$P(R\lambda/D) = P_0\{1 - \exp(-\pi^2/2n_L^2)\}.$$

Again, following the analysis of Reference 4, the power in the bucket for a non-diffraction-limited gaussion beam is given by

$$P(R\lambda/D) = P_0 \exp(-\sigma_L^2) \{1 - \exp(-\pi^2/2)\}$$

assuming all of the quality degradation can be characterized as a scattering loss. Equating these expressions and solving for σ_L yields,

$$\sigma_L = \left\{ -\ln \left[\frac{1 - \exp(-\pi^2/2n_L)}{1 - \exp(-\pi^2/2)} \right] \right\}^{1/2} . \tag{2}$$

Intuitively it would seem that both of these approaches should yield approximately equivalent results. Quantitatively however, substantial differences were found. These are illustrated in Figure 2.2 which compares the phase distortion computed from Equations (1) and (2). The phase distortion based on matching the peak intensity reduction is always considerably higher than that based on matching the power-in-the-bucket, e.g., over a factor of 2.5 for a 1.5 times diffraction-limited input beam. The reasons for these differences are not clear. One possible explanation is the equivalence of wavelength and power scaling methods of defining peak intensity reduction. It was found during previous work under this contract (Reference 1) that power scaling was always more pessimistic in its predictions of the beam quality than wavelength scaling. Therefore, matching the peak intensity based on a method that is equivalent to power scaling might be expected to produce more pessimistic results (i.e., higher σ_L) than matching the power-in-the-bucket based on wavelength scaling.

Whatever the reasons for the differences, we recommend the use of Equation (2) because the power-in-the-bucket is a more meaningful measure of laser performance than peak intensity reduction. The latter suffers from its sensitivity to defocusing errors and difficulty in experimental measurement.

2.1.2   Aerodynamic Window

The first component in the optical train is the aerodynamic window isolating the optical cavity of the laser
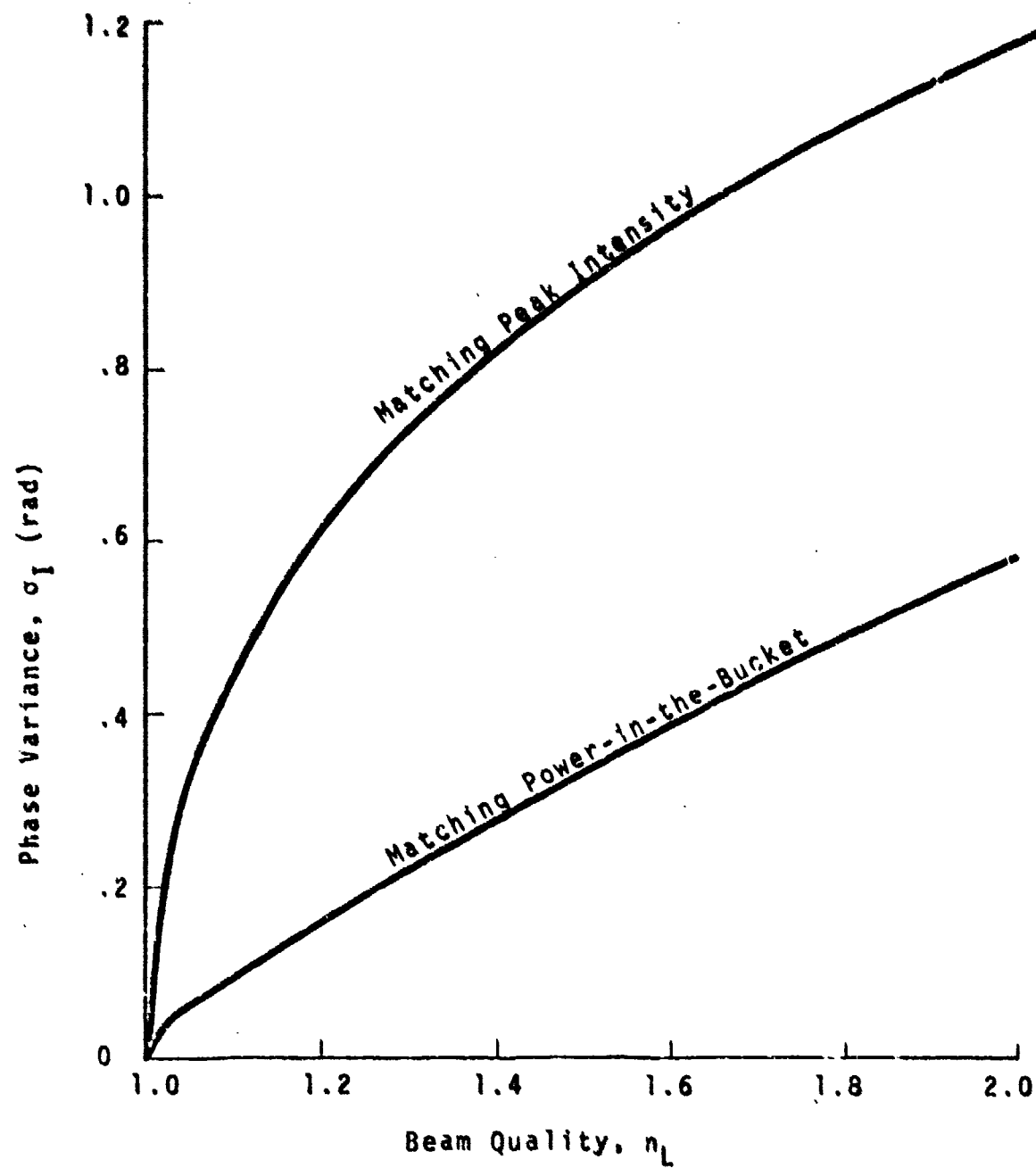
Figure 2.2.   Comparison of Input Beam Quality
Specifications

from the atmosphere. Basically there are two types of aerodynamic windows currently being considered for HEL applications: (1) focused and (2) unfocused. In both cases, if the window is properly designed, there should be little or no power loss when the beam passes through it. In addition, it is also assumed that no spherical distortion to the phase front will be induced by the aerodynamic window. The shock waves supporting the pressure rise and the turbulence generated by the aerodynamic window will, however, induce a loss in the beam quality. An expression for this loss is given by (Reference 4)

$$\Delta I/I = 2.84 \times 10^{-10} \left(\frac{\Delta\rho}{\rho_s} \frac{D_B}{\lambda} \right)^2$$

where $\Delta\rho$ is density change across the shear layer and ρ_s is a reference density at STP. Again this formulism of beam quality degradation is not convenient for use in the model and is converted into an equivalent phase distortion, σ_{aw}^2 by use of the Strehl formula (Reference 4):

$$\Delta I/I \approx \sigma_{aw}^2.$$

Solving for the phase distortion yields

$$\sigma_{aw} = 1.69 \times 10^{-5} \left(\frac{D_B}{\lambda} \frac{\Delta\rho}{\rho_s} \right).$$

A typical value of σ_{aw} for a 10 cm beam from a chemical laser ($\lambda = 3.8$ μm), assuming $\Delta\rho/\rho_s = 0.25$ for the density variations, is $\sigma_{aw} = 0.11$ radians. This corresponds to an intensity reduction of $\Delta I/I \approx 1.2\%$.

For the focused aerodynamic window, the beam diameter will typically be very small (<0.1 cm) so that the phase distortion can be neglected, i.e., $\sigma_{aw} \approx 0$.

2.1.3 Beam Clipper

For HEL systems in which the laser device and the pointer/tracker are not closely coupled, a beam clipper or scraper will probably be employed near the pointer/tracker to control the size of the high power beam entering the transmitter. The beam clipper will influence both the power available at the transmitting optic and the beam quality, the latter by limiting the maximum diameter at the transmitting optic.

The loss in power at the beam clipper is due primarily to diffractive spreading of the beam as it propagates between the aerodynamic window and the beam clipper. In general, the diffractive spreading will depend upon the phase and amplitude aberrations in the input beam profile. An accurate assessment of the actual losses requires a detailed calculation involving numerical solutions of the Fresnel diffraction integral or spatial frequency approaches to optical propagation (i.e., Fourier Optics). These techniques are very time consuming and were not considered as viable candidates for the "simplified" model. Instead, an empirical approach based on curve fits of available data in the literature was taken. Unfortunately very little data were available for examination. Only two sources were found (References 4 and 7). The data obtained from these sources are illustrated in Figure 2.3 which shows the variation in power diffracted into the geometric shadow of a uniformly illuminated aperture as a function of the propagation distance from the aperture. The AFWL data were calculated for a one-dimensional beam profile while the HAC (Hughes
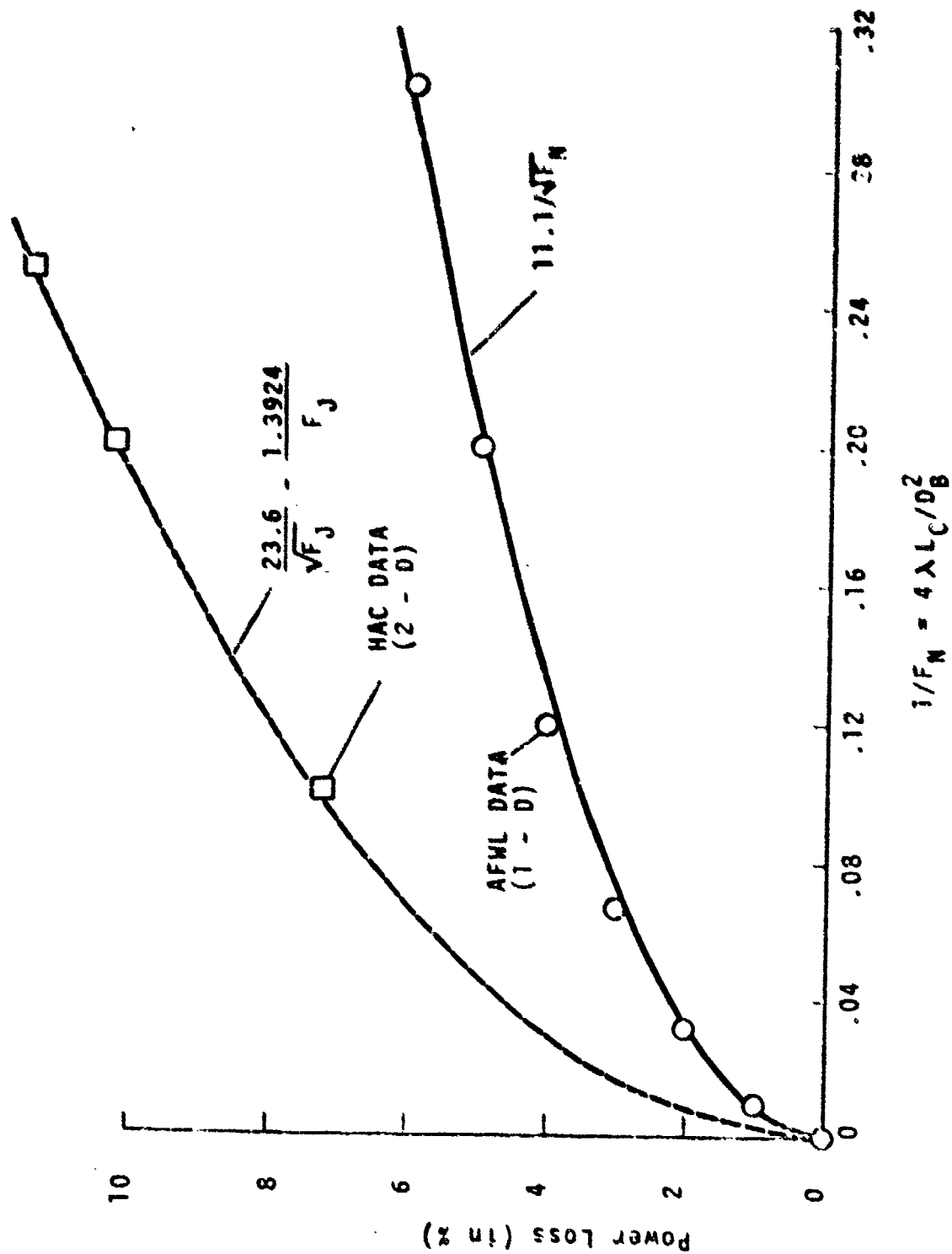
Figure 2.3. Diffractive Spillover Losses

Aircraft Company) calculations were performed for a round
beam. Therefore, the data must be adjusted for these
differences before a direct comparison can be made.

Intuitively one would expect a factor of two
difference between the data based on simple geometrical
arguments. For example, a square beam profile would have
twice the loss of a one-dimensional profile because of the
two additional edges. For a round beam, however, the ratio
is not quite as straightforward. Assuming circular symmetry,
the fractional power loss is

$$\Delta_{2-D} = \frac{2\pi \int_a^\infty I(\sigma)\,\sigma d\sigma}{\pi a^2 I_0}$$

where a is the radius of the aperture and I_0 is the initial
intensity. The major contribution to the integral occurs
near the edge of the aperture. Thus over this region the
radius can be taken as being approximately constant (= a)
and removed from the integral without affecting its value,
i.e.,

$$\Delta_{2-D} = \frac{2}{a I_0} \int_a^\infty I(\sigma)\,d\sigma .$$

For the one-dimensional beam profile the fractional power
loss is given by

$$\Delta_{1-D} = \frac{\int_a^\infty I(x)\,dx\ (1)}{a\ I_0\ (1)}$$

so that if one further assumes that the intensity profiles at the aperture plane are the same in either case, i.e., $I(r) = I(x)$, then one again gets a factor of two difference between the power losses.

The actual ratio indicated by the data was somewhat higher than a factor of 2 as shown by the corresponding curve fits of the data. Both sets of data correlated very well as a function of the reciprocal of the square root of the Fresnel number. However, the proportionality constant for the HAC data was found to be 23.6 versus 11.1 for the AFWL data.

In order to use these results in the optical train model, the power loss was assumed to be related to an effective increase in the beam diameter at the aperture plane, i.e.,

$$\frac{D_B}{D_{B_o}} = (1 - loss)^{1/2} 1 - \frac{0.112}{\sqrt{F_N}}$$

where D_{B_o} is the new diameter of the beam at the beam clipper station and $F_N = D_B^2/4\lambda L_C$ is the propagation Fresnel number. It was also assumed, for the case of an obscured beam, that the hole in the beam filled in as much as the diameter of the hole would grow were it a uniformly illuminated aperture (i.e., Babinet's Principle). Thus the inner diameter of the obscured beam, D_{Bi}, is computed by

$$D_{Bi} = \varepsilon D_B (1 - 0.112/\varepsilon \sqrt{F_N}).$$

If D_c is the diameter of the beam clipper, then the power transmission through the aperture is

$$T_c = \begin{cases} 1.0 & \text{if } D_{B_0} \leq D_c \\ (D_c/D_{B_0}) & \text{if } D_{B_0} > D_c \end{cases}.$$

In the latter case, the beam diameter is set equal to the clipper diameter for the remaining calculations in the model.

2.1.4   High Power Mirrors

The mirrors in the optical train will affect all the performance parameters. Although it is not necessary we assume that all of the mirrors are identical in order to reduce the number of inputs.

A mirror alters the amplitude of the beam by absorbing a fraction of the incident radiation. For a series of N mirrors each having a surface reflectivity R, the transmission factor is

$$T_M = R^N.$$

It should be noted that in the present analysis N includes all of the mirrors in the optical train, i.e., relay, steering, secondary and primary.

The beam quality degradation is due to (1) surface roughness and manufacturing errors in the mirror figure, and (2) surface distortions due to absorption of power from the incident beam. The former are independent of the power in the beam while the latter is a function of both the power and the irradiance distribution. In addition, if

cooled mirrors are used, there will also be distortions
induced by the pressure variations inside the coolant
passages. However, these distortions will depend upon the
details of the mirror construction and their characteriza-
tion is felt to be beyond the scope of this model. There-
fore, for this analysis, distortions of this type will be
included in (1) above.

The beam quality degradation induced by the mirrors
is incorporated into the optical train model through an
equivalent phase variance, σ_M where

$$\sigma_M^2 = N\sigma_f^2 + \left[(N - 1)\ \sigma_I + \sigma_I/M^2\right]^2.$$

The first term on the right hand side of the above expres-
sion represents the uncorrelated sum of the phase distortion
due to fabrication errors such as surface roughness, figure
error, coolant passage distortion, etc. The remaining terms
represent the correlated sum of the irradiance mapping phase
distortion. The distortion of the primary mirror is reduced
by the square of the magnification of the beam expander to
account for its reduced thermal loading.

In practice, σ_f is not known but is instead specified
as a tolerance on the manufacturing process. Therefore,
for modeling purposes this parameter was left to the user
to specify.

The approach taken to model σ_I was to assume that
the distortions scale directly with the irradiance fluctua-
tions. That is,

$$\sigma_I = KI_{rms}$$

where K is a constant which depends upon the physical parameters of the mirror, the cooling scheme, etc. If we assume that the peak to peak intensity fluctuations specified in the input beam description are uniformly distributed and random in character, then

$$I_{rms} = \frac{I_{ave}}{\sqrt{12}} \left(\frac{\Delta I}{I_{ave}}\right)$$

where, for a circular beam,

$$I_{ave} = \frac{4\ P_L}{\pi\ D_B^2}$$

Expressions for the evaluation of K depend upon whether the mirror is water cooled or not, i.e., for cooled optics

$$K(m^2/watt) = 5 \times 10^{-14}\ (1 - R)\ (2\pi/\lambda)$$

whereas, for uncooled optics

$$K = 4\pi\ (1 - R)\ \alpha\Delta t/\lambda C\rho$$

where

α = the thermal expansion coefficient of the mirror material

C = the specific heat of the mirror material

ρ = density of the mirror material.

The expression for cooled optics is based on the
NPT/Chemical Laser Compatibility Study conducted by
Hughes Aircraft Company for NSWC (Reference 8) in which
similar expressions were employed to compute the phase
distortion caused by the NACL irradiance profile. The
expression for uncooled optics is based on a simplified
one-dimensional heat transfer analysis (Reference 9).

Local surface distortion is not the only performance
degrading factor caused by the finite absorptivity of the
mirrors. A bending distortion is also induced by the
differential growth of the front and rear mirror surfaces.
For properly designed, cooled mirror configurations, this
distortion can be kept small. However, for uncooled mirrors,
it may be important.

To first order, the bending distortion is primarily
a function of the total beam power and not the irradiance
distribution. In addition it produces mostly a spherical
phase front distortion. Thus in the optical train model,
we compute this distortion mode as a beam divergence instead
of a quality loss since, in theory, it could be corrected by
the focusing optic (if detected).

For an uncooled mirror that was initially flat, the
change in the focal length with time can be approximated
as (see Reference 9)

$$f = \frac{D_B^2 \, \ell \, \cos \Theta}{2.44 \, P_L \, (1 - R) \, \alpha} \left(\frac{D \rho K}{\Delta t} \right)^{1/2}$$

where

ℓ is the mirror thickness

Θ is the beam angle of incidence on mirror

K is the thermal conductivity of the mirror
   material

f is the focal length of the distorted mirror.

The mechanism by which the defocusing errors
induced by the individual mirrors are accumulated through-
out the optical train is explained later.
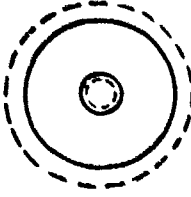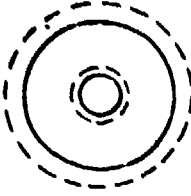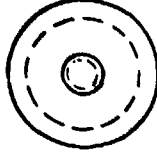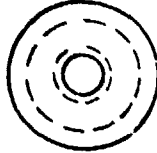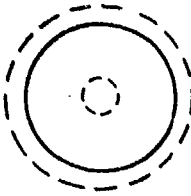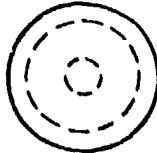
2.1.5   Beam Expander

In the formulation of the beam expander model, we
allow for two types: (1) an on-axis or (2) an off-axis
system. Either type system affects the available power
at the transmitter, the beam quality, beam jitter and beam
divergence. A discussion of the methodology for computing
the transmission factor and beam quality is given below.
The beam jitter and divergence are discussed in a later
section.

The power transmission through the beam expander
is computed by projecting the exit aperture (defined by
the user) onto the plane of the beam clipper station.
Simple geometry then allows one to compute the power lost
due to a mismatch between the beam diameters and exit
aperture diameters. The formulas are illustrated in
Table 2.1 for both the on-axis and off-axis cases.

The beam quality is not affected by the off-axis
system except to the extent that the limiting diameter is
$MD_{B_o} \leq D_t$ for spot size calculations at the target plane.
This is also true of the on-axis case. However, the on-
axis system also introduces a central obscuration ε, which
reduces the beam quality. The expressions used in the
model to compute the final obscuration of the beam leaving
the optical train are also given in Table 2.1.

Table 2.1.   Summary of Beam Expander Transmissions and Obscuration Calculations

TYPE	GEOMETRY	TRANSMISSION	OBSCURATION
ON AXIS		$\dfrac{D_o^2 - D_i^2}{D_{B_o}^2 - D_{B_i}^2}$	D_i/D_o
		$\dfrac{D_o^2 - D_{B_i}^2}{D_{B_o}^2 - D_{B_i}^2}$	D_{B_i}/D_o
		$\dfrac{D_{B_o}^2 - D_i^2}{D_{B_o}^2 - D_{B_i}^2}$	D_i/D_{B_o}
		1.0	D_{B_i}/D_{B_o}
OFF AXIS		$(D_o/D_{B_o})^2$	D_{B_i}/D_o
		1.0	D_{B_i}/D_{B_o}

The effect of the obscuration on the beam quality is again computed by relating it to an equivalent phase distortion. This relationship was derived empirically based on the results of the previous work under this contract (Reference 2), and is illustrated graphically in Figure 2.4. Within the computer code, this relationship is represented by a third order polynomial developed from a "least-squares" regression analysis of the data presented in Figure 2.4. Also shown on the figure is the effective scale size of the phase distortion. Its use in the model will be explained below.

2.1.6 Exit Aperture

Provisions were also made in the optical train model for an exit aperture downbeam of the pointer/tracker. It can be either a material window or open port, with an aerodynamic curtain protecting the optics from the environment, based on user specified option parameters.

In either case the loss in power through this exit aperture will be

$$T_E = e^{-\beta L_W} (1 - A_S/A_B)$$

where

β = absorption coefficient of material window

L_W = thickness of material window

A_S = area of struts supporting window or secondary mirror in the case of an on-axis beam expander

A_B = beam area $(\pi M^2 D_{B_O}^2 /4)$.

Equivalent Scale Size, W_2/l_0

6.0 5.0 4.0 3.0 2.0 1.0

$\dfrac{t}{w} = 0.0$

Obscuration Ratio, θ

.5 .4 .3 .2 .1 0
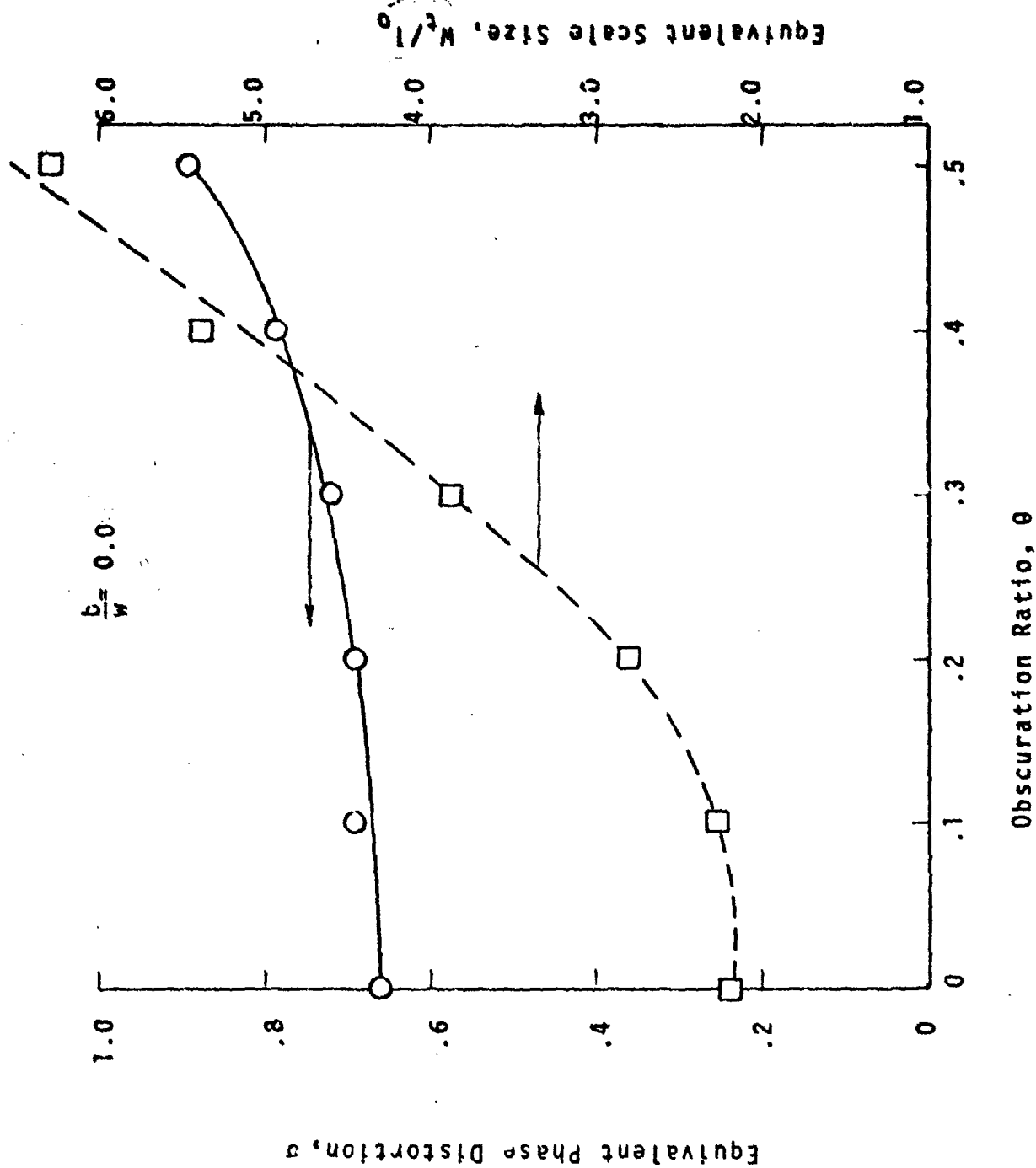
Figure 2.4. Beam Quality Loss Due to Central Obscuration in Terms of θ and W_t/l_0

1.0 .8 .6 .4 .2 0

Equivalent Phase Distortion, σ

Note that an open port can be simulated by setting $\beta = 0$.

For simplicity, the phase distortion induced by the material window is assumed to be proportional to the local intensity fluctuations in the beam profile. That is

$$\sigma_w = \left(\frac{2\pi}{\lambda}\right) \frac{\beta \Delta t L_w}{\rho c} \left[(n - 1) \alpha + \frac{\partial n}{\partial T}\right] \frac{I_{rms}}{M^2}$$

where (in addition to those parameters previously defined) n is the refractive index and T is the temperature. The magnification appears because of the assumed location of the window downstream of the beam expander. In order to minimize the number of inputs to the model, the material constants were lumped into a single parameter defined as

$$\gamma = \frac{1}{\rho C} \left[(n - 1) \alpha + \frac{\partial n}{\partial T}\right]$$

which varies between $4 \times 10^{-12} \, m^3/j$ for the fluoride windows aF$_2$, MgF$_2$, SrF$_2$) to $15 \times 10^{-12} \, m^3/j$ for the salt windows (NaCl, KCl). A value of $5 \times 10^{-12} \, m^3/j$ was hardwired into the model as being representative of current window technology.

The presence of struts in the beampath will also cause a reduction in the beam quality. To first order, this loss will be directly proportional to the area of the beam blocked by the struts. Consider, for example, the on-axis intensity which, in the context of scalar diffraction theory, is given by the integral of the complex field leaving the transmitting aperture, i.e.,

$$I(o) \sim \left[\iint u(x,y) \, dx \, dy\right]^2.$$

Thus, for a constant field aperture strength, the integral is simply the area of the clear aperture. That is

$$I(o) \sim (A_B - A_S)^2$$

so that the intensity reduction relative to no struts is simply

$$\frac{I(o)}{Io} = \left(1 - \frac{A_S}{A_B}\right)^2 = T_S \ (1 - A_S/A_B).$$

For modeling purposes, this intensity reduction was considered to be separable into (1) a power loss due to the transmission of the aperture, T_S, and (2) a beam quality loss characterized by wide angle scattering, $(1 - A_S/A_B)$. The latter can be related to an equivalent phase distortion via the Strehl equation

$$\sigma_S = (A_S/A_B)^{\frac{1}{2}} .$$

The phase distortion induced by an open port is not intensity dependent but instead a function of the turbulence level inside the beam expander and aerodynamic curtain. Because of the presence of turbulence, this effect is treated as an additional source of beam jitter in the model. The magnitude of the jitter is estimated from (Reference 8)

$$\theta_J = 2.14 \times 10^{-7} \ \left[\frac{L_e^3 \ \Delta T^6}{\lambda \ D_t^2}\right]^{1/5}$$

where L_e is the path length through the beam expander and ΔT is the magnitude of the temperature fluctuations within the beam expander. Some representative values of the jitter are illustrated in Figure 2.5 for a 0.7 meter transmitter diameter. For example, a $1^{\circ}C$ temperature fluctuation produces approximately 4.5 µrad of beam jitter for a 3.8 µm wavelength beam.

2.2   ASSESSMENT OF OVERALL PERFORMANCE

The previous discussion was primarily concerned with the influence each of the elements has on the characteristics of the laser beam as it traverses the optical train. In the following section we show how these individual effects are accumulated to arrive at an overall assessment of system performance.

2.2.1   Transmitted Power

The power available at the transmitting optic is simply the input power from the laser device modified to account for all of the power losses that have occurred along the optical train. That is

$$P_t = T \, P_L$$

where T is an overall transmission factor. Since the power losses are multiplicative, the overall transmission factor is

$$T = (T_c) \, (T_M) \, (T_{BE}) \, (T_E)$$

Diameter = 0.7 m
Length = 2.0 m
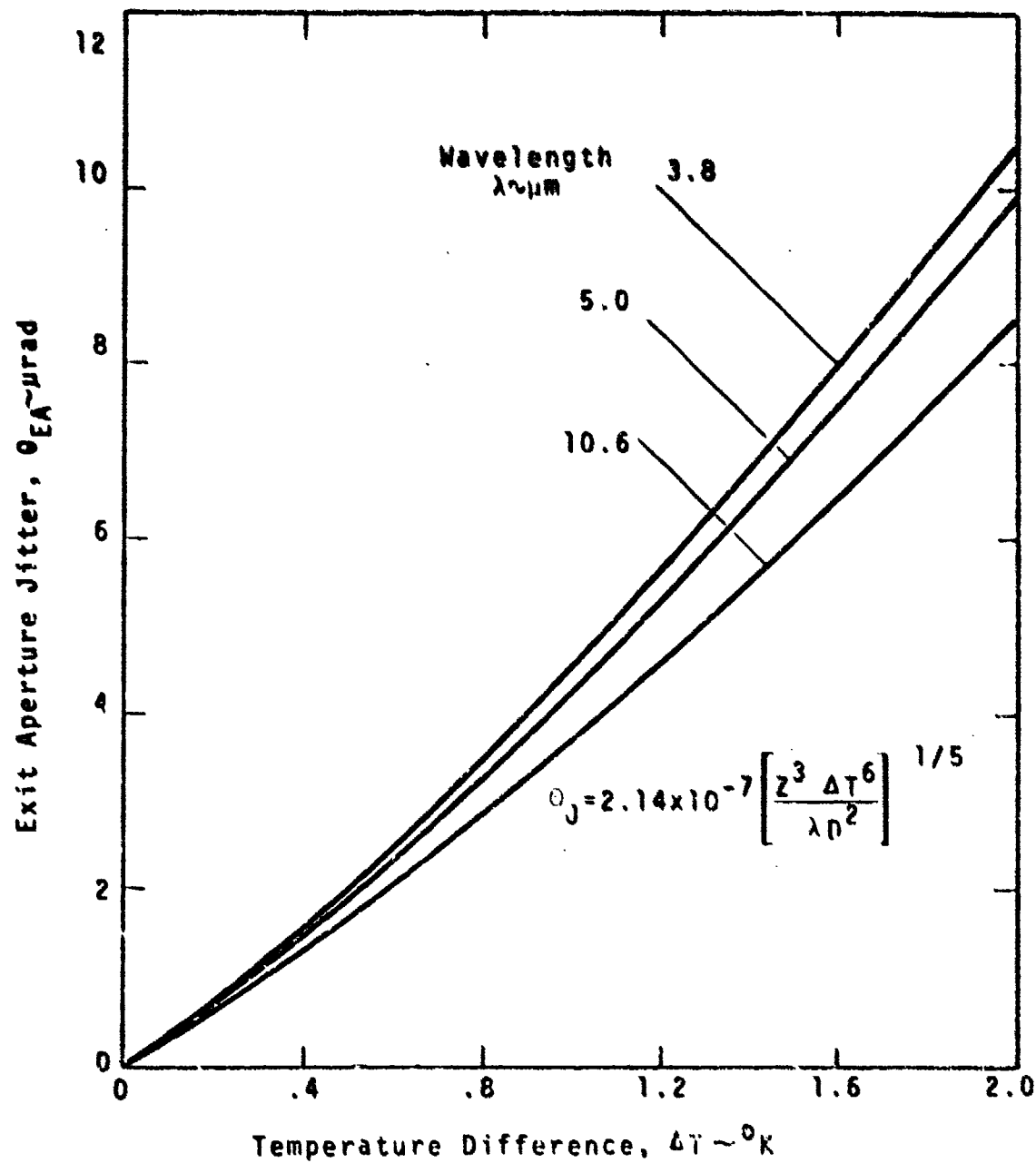
Figure 2.5. Effects of Exit Aperture Temperature Fluctuations on Beam Jitter

where T_c is the transmission factor of the beam clipper, T_M is the transmission factor of all the high power mirrors, T_{BE} is the transmission factor of the beam expander, and T_E is the transmission factor of the exit aperture. Formulas for all of these factors were given previously.

2.2.2 Beam Quality

The quality of the beam at the transmitting optic is characterized by the two beam quality parameters, m_1 and m_2 (see Reference 1 and Section 4.3 of this report). Unfortunately, the calculation of m_1 and m_2 is not simple. The basic problem is to combine the effect of all the quality degrading factors occurring within the optical train. This is somewhat complicated because the phase distortions induced by the individual components do not add up in a straightforward manner but instead depend, in a complicated manner, upon the distribution as well as the magnitude of the phase distortion. For example, a "smooth" distortion behaves differently than a very "rough" distortion even though their magnitudes are the same.

To circumvent this problem, a statistical approach is used within the model to accumulate the phase distortions. This approach is somewhat loosely based on the theoretical investigations of nondiffraction-limited gaussian beams by B. Hogge at the AFWL. Briefly, the approach is to consider the overall beam profile at the focal plane as being composed of two gaussian beam profiles of different relative amplitudes and widths. That is, a certain fraction of the energy in the beam is propagated completely unaffected by the phase distortion, i.e.,

$$I_u(r) = e^{-\sigma^2} \exp\left(-\frac{2r^2}{w_f^2}\right) I_o$$

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where w_f is the diffraction limited waist parameter, I_0 is the on-axis intensity and σ^2 is the variance of the phase distortion (assumed to a gaussian random variable). The remaining energy is smeared or spread by the phase distortion into a somewhat larger beam profile, i.e.,

$$I_s(r) = (1 - e^{-\sigma^2}) \left(\frac{w_f^2}{w_f^2 + 2\Theta^2 f^2} \right) \exp \left(\frac{-2r^2}{w_f^2 + 2\Theta^2 f^2} \right) I_0$$

where Θ is the angular spread of the scattered beam.

The problem thus reduces to characterizing the overall phase variance, σ, and beam spread parameters, Θ, that "best" model the summation of all of the phase distortions in the optical train.

A true characterization of σ and Θ is, in reality, not possible. Some theoretical arguments can be made for isolated phase ditributions such as the random gaussian noise model investigated by Hogge. In the real world, however, optical systems do not produce such amiable distortions. Nevertheless, using these results as being at least qualitatively correct, we compute the total phase distortion as simply the uncorrected sum of each of the individual distortions, i.e.,

$$\sigma^2 = \sigma_L^2 + \sigma_{AW}^2 + \sigma_M^2 + \sigma_{BE}^2 + \sigma_S^2 + \sigma_W^2.$$

Instead of computing the beam spread, Θ, it is more convenient to compute an effective scale size or correlation length of the overall phase distortion, L. This scale size is related to the beam spread via $\Theta^2 = (\lambda/\pi L)^2$. In the

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aforementioned work of Hogge, it was noted that the
effective correlation length for a number of sources of
phase distortion was found to be an average of the correla-
tion lengths of the individual sources, each weighted by
its respective variance. Again, taking the inductive leap,
we compute L from

$$L = \frac{1}{\sigma^2} \left[\ell_L \sigma_L^2 + \ell_{AW} \sigma_{AW}^2 + \ell_M \sigma_M^2 + \ell_{BE} \sigma_{BE}^2 + \ell_S \sigma_S^2 + \ell_W \sigma_W^2 \right].$$

In practice very little is known about the magnitude of
the scale sizes characterizing the individual components.
Therefore, for the present model, we have made some addi-
tional assumptions regarding their respective sizes. For
example, the irradiance mapping phase distortions such as
σ_I and σ_W are assumed to have the same scale size as the
intensity fluctuations in the input beam profile. For
other components, such as the laser device, the aerodyanmic
window and the struts, we assume that the scale size is
zero. In effect this is assuming that each of these com-
ponents scatters the energy in the beam beyond a usable
radius in the focal plane and therefore is somewhat conserva-
tive. The scale size of the beam expander was determined
empirically since the effect of obscuration on the near-
field beam profile was readily calculated (see Figure 2.4).
Within the model this relationship is represented by a
third order polynomial.

The computed values of the phase variance and
scale size are used to evaluate the power distribution at
two radial positions in the far-field, namely $r = w_f$ and
$r_2 = 2w_f$. These power points are then used to generate
the beam quality parameters m_1 and m_2. The procedure for
doing this is outlined in Reference 1.

2.2.3 Beam Jitter

The beam jitter is accumulated throughout the optical train by assuming that the sources of beam jitter are independent of each other. Thus they may be root-sum-squared to get the total jitter. The primary consideration for the beam jitter calculation is whether or not the source of the jitter is upbeam or downbeam of the beam expander. The beam expander reduces the jitter by a factor of $1/M^2$ where M is the magnification.

The sources of beam jitter considered by the model are

- Tracking jitter, Θ_{TR}
- Boresight jitter, Θ_{BS}
- Autoalignment system jitter, Θ_{AA}
- Servo jitter, Θ_S
- Device jitter, Θ_L
- Exit aperture induced jitter, Θ_E.

The jitter of the input beam and the jitter induced by the beam steering mirror in the autoalignment system are assumed to occur before the beam expander. The remaining jitter sources are assumed to occur after the beam expander. Thus the total jitter leaving the optical train is given by:

$$\sigma_J = \{ \Theta_{TR}^2 + \Theta_{BS}^2 + \Theta_S^2 + \Theta_E^2 + (\Theta_L^2 + \Theta_{AA}^2)/M^2 \}^{\frac{1}{2}}.$$

2.2.4 Beam Divergence

The beam divergence represents the spherical phase curvature in the beam as it enters the transmitting optic and results in a larger spot size at the target than one

would expect had the beam been collimated when it entered the transmitting optic. As an example, consider a collimated ideal gaussian beam which has been focused to produce a spot size of w_f (actually a radius to the e^{-2} intensity point) at a target. If the beam is instead diverging (or converging) with a radius of curvature $-R_B$ $(+R_B)$ as it is reflected from the same transmitting optic, the new spot size w_f' is larger than the original by

$$\left(\frac{w_f'}{w_f}\right)^2 = 1 + \left(\frac{\pi D_B^2}{4\lambda R_B}\right)^2$$

where D_B is the (e^{-2}) diameter of the ideal gaussian beam and λ is the wavelength. For example, 0.1λ spherical phase error will increase the spot size approximately 20% for a 100 cm diameter optic transmitting at $\lambda = 3.8$ μ. For the present study we assume that any phase curvature in the output beam from the optical train behaves in a similar manner.

The change in the curvature of the phase front of the beam as it propagates through the optical train is computed by employing a simplified geometric optics calculation through the optical elements preceding the beam expander. The usual simplifying assumptions, i.e., paraxial rays, thick lenses, etc., are made in order to make the calculation tractable.

Following the ray matrix approach of Reference 10 we first obtain the equivalent ray matrix of the optical train illustrated in Figure 2.6 by multiplying together the individual ray matrices of the individual elements, i.e.,
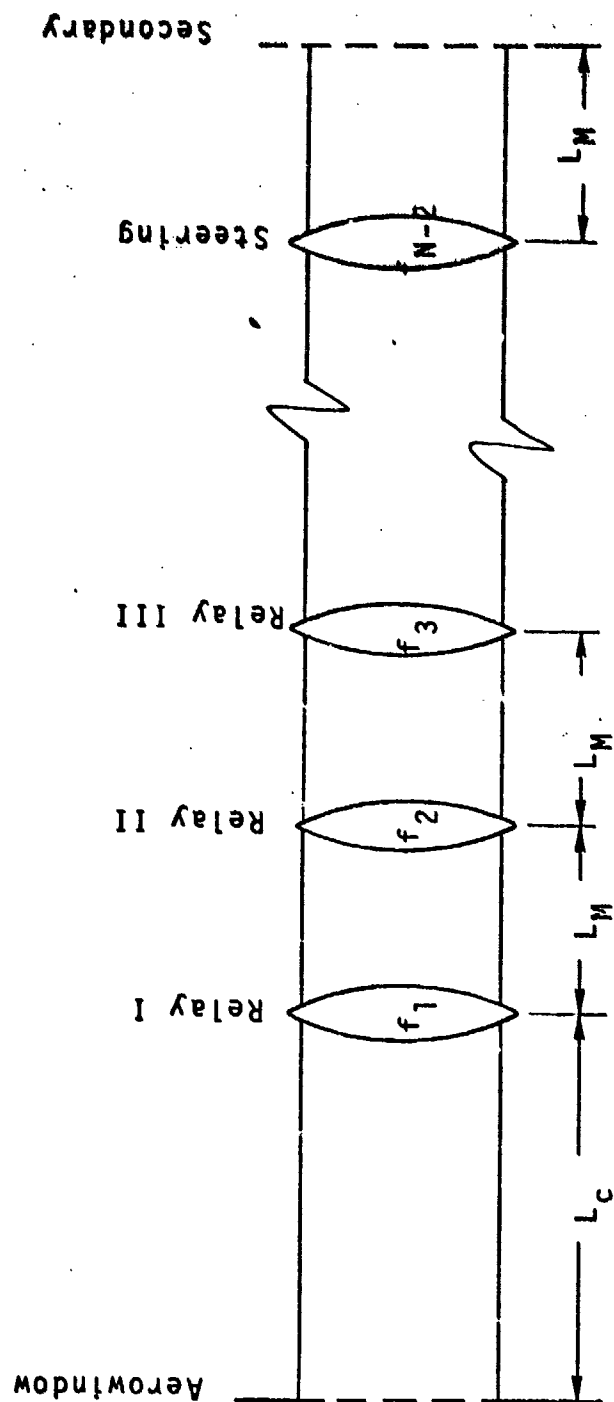
Figure 2.6. Simplified Optical Train Employed in Defocus Calculations

$$
\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & L_M \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f_{N-2} & 1 \end{bmatrix} \cdots \begin{bmatrix} 1 & 0 \\ -1/f_2 & 1 \end{bmatrix} \begin{bmatrix} 1 & LM \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f_1 & 1 \end{bmatrix} \begin{bmatrix} 1 & L_C \\ 0 & 1 \end{bmatrix}
$$

where (going from right to left) the first matrix represents
the propagation distance between the aerodynamic window and
the beam clipper, the second matrix represents the reflec-
tion of the beam from the first relay mirror in the optical
train, the third matrix represents the propagation distance
between the first relay mirror and the second relay mirror,
the fourth matrix represents the reflection of the beam
from the second relay mirror, and so on until the beam is
incident upon the secondary mirror. At this point we
assume that the beam expander simply expands the beam by
the specified magnification. The cur ture of the phase
front at this point, R_B, is related to the phase front
curvature of the input beam, R_L, by

$$
R_B = M \left(\frac{AR_L + B}{CR_L + D} \right).
$$

The computed value of R_B is then used to compute the new
spot size of the focused beam. In order to transfer this
information to the propagation model, the beam quality
parameter, m_2, which characterizes the spread of the beam
profile in the absence of other effects, such as thermal
blooming, turbulence and beam jitter, is internally adjusted
by the model to reflect the increased beam spread, i.e.,

$$
(m_2)_{final} = \sqrt{1 + \left(\frac{\pi D_B^2}{4\lambda R_B} \right)^2} \quad (m_2).
$$

2.3 SAMPLE CALCULATIONS

As an illustration of how the optical train influences the performance of a laser system, we present below a sample calculation for the optical train schematically illustrated in Figure 2.7.

The laser device is assumed to be operating in an unstable confocal resonator mode with the power coupled out of the device via a scraper mirror located in front of the convex optic of the resonator. Accordingly, the output beam contains a central obscuration. The parameters assumed for this beam are:

```
Beam Diamter  = 0.1 meters
Power         = 400 kw
Wavelength    = 3.8 microns
Obscuration   = 0.5
```

In addition, it is assumed that the beam is essentially collimated ($R_L = \infty$) and contains peak-to-peak intensity fluctuations that are 50 percent of the average intensity ($\Delta I/I_{ave} = 0.5$). The scale size of these fluctuations is taken to be 1 cm or $\ell_I/D_B = 0.1$. We also assume that the quality of the beam leaving the device is characterized as being 1.2 times diffraction-limited ($n_L = 1.2$). This corresponds to an equivalent rms phase distortion in the beam of $\sigma_L = 0.16$ radians or about $\lambda/40$ (see Figure 2.2).

The output beam from the laser device is focused through an aerodynamic window to a collimating mirror. Since the beam size is very small (typically < 0.1 cm) at the aerodynamic window, we neglect any phase distortion induced by the aerodynamic window (i.e., $\sigma_{aw} = 0$).
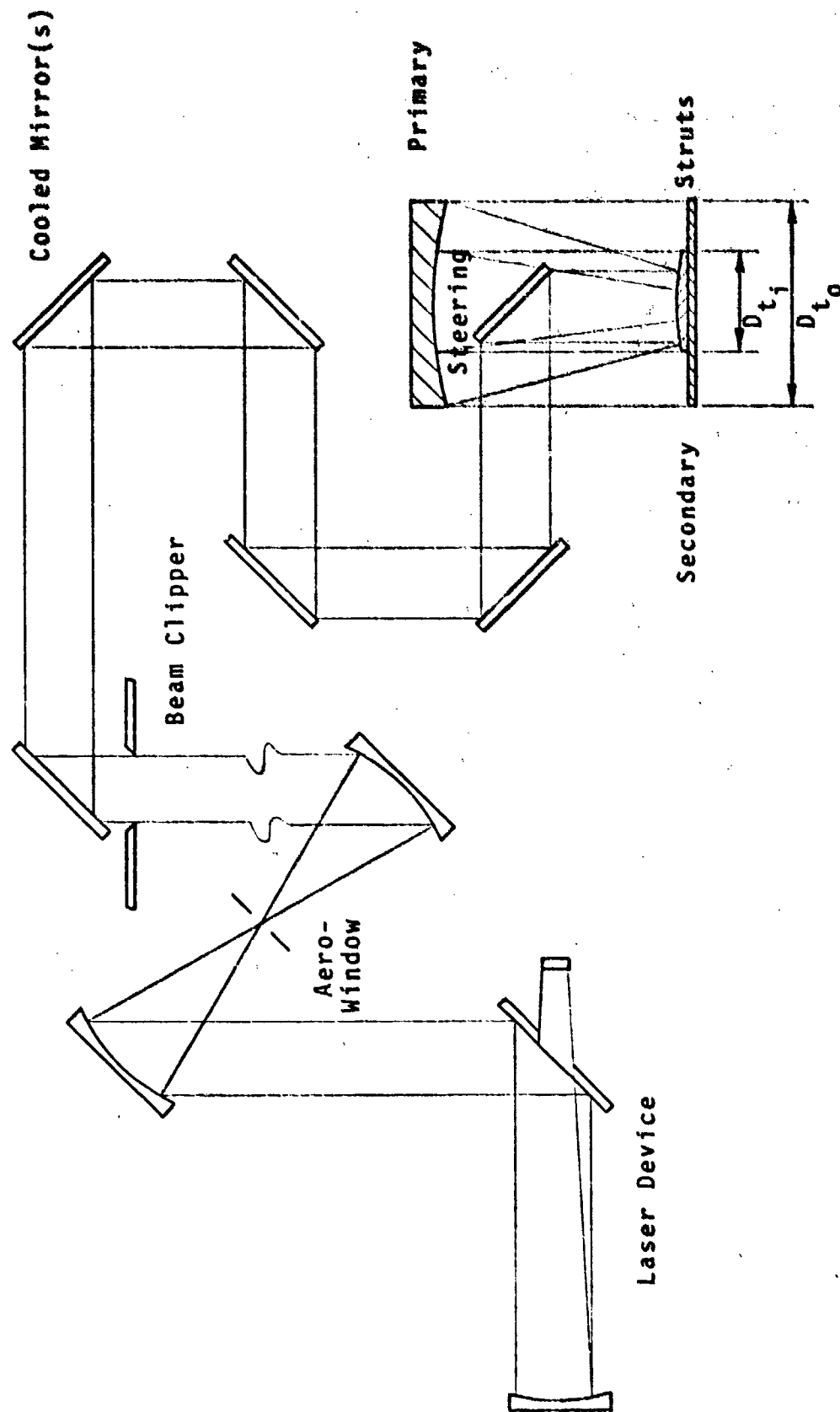
Figure 2.7. Schematic of Optical Train for Sample Calculations

For the example, we assume that the beam expander is located 50 meters from the aerodynamic window. Over this distance, diffraction effects cause the beam to expand somewhat. The Fresnel number for this propagation distance is

$$F_N = \frac{4D_B^2}{\lambda L_c} = 13.16$$

so that the beam diameters at the entrance to the beam expander are

$$D_{B_0} = \frac{D_B}{1 - 0.112/\sqrt{F_N}} = 0.103 \text{ m}$$

and

$$D_{B_i} = \left(\epsilon - \frac{0.112}{\sqrt{F_N}} \right) D_B = 0.047 \text{ m}.$$

In this example, we have assumed that the diameter of the beam clipper is 16 cm so that no power loss due to clipping occurs, i.e., $T_c = 1.0$.

The nine (9) mirrors employed in the optical train are assumed to be water cooled with a reflectivity of $R_i = 0.986$. We also take the fabrication error as being $\lambda_v/8$ where λ_v is 0.564 microns. Accordingly, the power lost to the beam due to the finite absorptivity of the mirrors is

$$T_M = (0.986)^9 = 0.88.$$

The phase distortion induced by each mirror depends upon the rms intensity fluctuations, which for the case being considered are

$$I_{rms} = \frac{4P_L}{\pi D_B^2} \quad \frac{\Delta I/I_{ave}}{12} = 7.35 \times 10^6 \text{ w/m}^2$$

so that

$$\sigma_I = 5 \times 10^{-14} (1 - R)(2\pi/\lambda) I_{rms} = 0.0085 \text{ radians.}$$

Combining this with the fabrication error yields (for all of the mirrors in the optical train)

$$\sigma_M = 9\sigma_f^2 + [8\sigma_I + \sigma_I/M^2]^2 = 0.3454 \text{ radians.}$$

The beam expander is an on-axis system of magnification. $M = 4.37$. The inner and outer diameters of the clear output aperture are $D_{t_o} = 0.7$ and $D_{t_i} = 0.252$ meters respectively. Since the beam entering the expander is not perfectly matched to the reduced clear aperture dimensions (i.e., $D_{t_o} = 0.16$ and $D_{t_i} = 0.576$), there is a power loss induced by the beam expander. From the geometry of the case being considered, this loss is computed to be approximately 13 percent or $T_{BE} \approx 0.87$. In addition, the beam expander has altered the obscuration of the input beam because of clipping. final obscuration of the beam leaving the beam expander is $\epsilon = 0.0576/10.3 = 0.558$. Note that the final obscuration is not the observation of the

telescope (D_{t_i}/D_{t_o} = 0.36) because the input beam was not large enough to fill the transmitting optic. The effective phase distortion of the actual beam is therefore much larger than one would compute based on the obscuration of the telescope. For the example being considered, this equivalent phase distortion is σ_{BE} = 0.72 radians.

The exit aperture was assumed to be an open port so that the only power loss is that due to blockage by the struts required to support the secondary mirror of the beam expander. Thus, T_E = 0.95. The quality loss due to the struts is

$$\sigma_s = (A_s/A_B)^{\frac{1}{2}} = 0.2236 \text{ radians.}$$

Within the model, the open port would also induce jitter into the beam. However, for the purposes of this example, we have ignored any performance loss caused by beam jitter.

Combining the above losses, we get for the overall transmission factor

$$T = T_C \cdot T_{BE} \cdot T_E = 0.727.$$

Thus, the power from the device that is available for propagation to the target is

$$P_t = 0.727 \, P_L = 290 \text{ kw.}$$

The total distortion is

$$\sigma = \left(\sigma_m^2 + \sigma_{BE}^2 + \sigma_S^2 + 0.433\right)^{\frac{1}{2}} = 1.06 \text{ rads.}$$

This phase distortion is characterized by a scale size

$$\frac{\ell}{D_B} = \frac{1}{\sigma^2} \left\{ \frac{\ell_{BE}}{D_B} \sigma_{BE}^2 + \frac{\ell_1}{D_B} \left[(N - 1)\sigma_1 + \frac{\sigma}{M^2} \right]^2 + 0.196 \right\} = 0.114$$

In terms of the two parameter descriptions of the beam quality employed by the model $m_1 = 0.3536$ and $m_2 = 1.1076$. For this example, there were no defocusing errors induced by any of the components in the optical train so that no adjustment was made to the beam spread parameter m_2. Note that the constraints in the last two equations (0.433 and 0.196) are needed to ensure the proper conversion of σ and $\frac{\ell}{D_B}$ to m_1 and m_2.

In order to quantify the impact of the optical train, we evaluate the power delivered to a particular spot in the focal plane, namely $r^* = f\lambda/D_{t_o}$. In the absence of atmospheric effects and beam jitter, this power is simply

$$P(r^*) = P_t m_1 \left\{ 1 - \exp\left[- \frac{\pi^2}{m_2^2} \left(\frac{D_B}{D_{t_o}} \right)^2 \right] \right\}$$

where D_B is the actual diameter of the beam on the transmitting optic, i.e., $D_B = M D_{B_0} \leq D_{t_o}$.

The results of this calculation for the example being considered is shown in Figure 2.8 along with some additional calculations made for various input beam diameters. For the conditions described above, only 83 kw of the initial 400 kw are delivered to the target. Note, however, that by expanding the input beam a significant increase in power can be achieved. The initial beam size of 10 cm was too small to effectively use the entire diameter of the transmitting optic. Hence, the beam profile at the target was
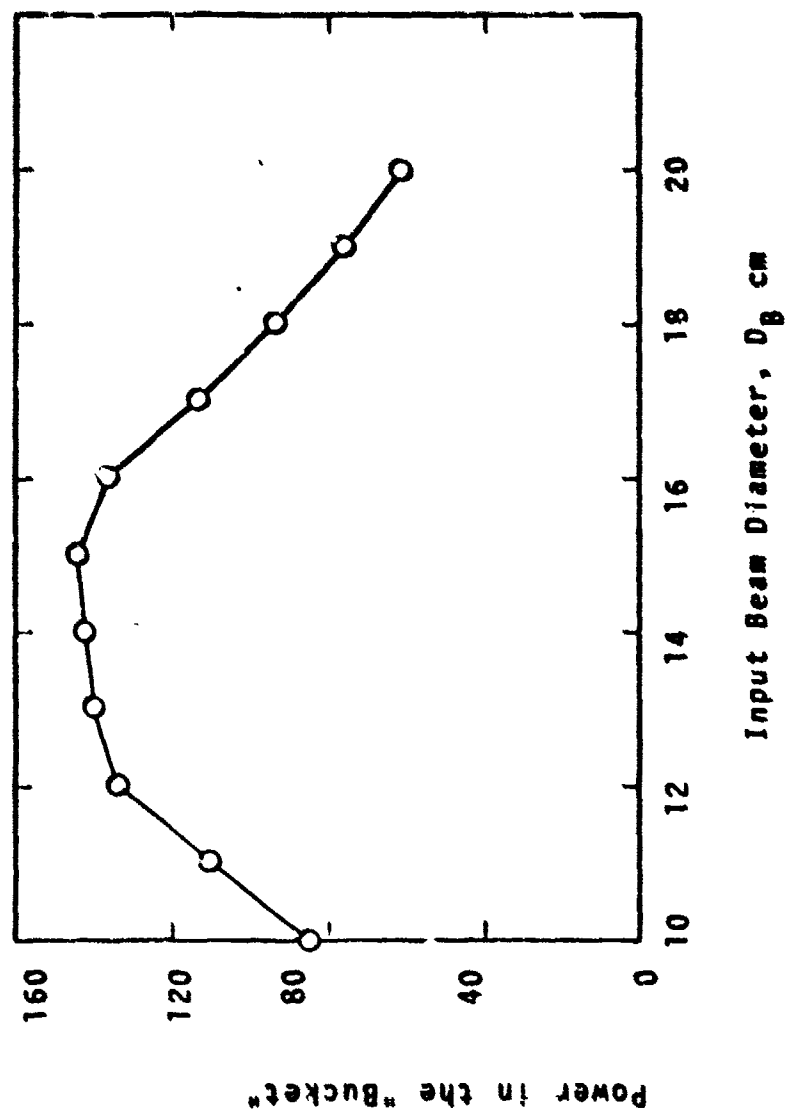
Figure 2.8. Results of Sample Calculations

larger than it should have been. In addition, because of
the mismatch of device output beam and beam expander clear
aperture, a significant power loss occurred. As the beam
diameter is allowed to increase, both of these effects are
reduced. Of course, at the point where the beam begins to
spill-over onto the beam clipper, the near-field power is
again reduced resulting in the performance fall-off shown
in the figure.

It is recognized that a true performance evaluation
cannot be made without including the propagation effects
between the transmitter and target plane. However, the
example does point out the necessity of including the effects
of the optical train in any application study, since it
indeed has a substantial impact on the near-field characteris-
tics of the beam. In addition, the model also should pro-
vide some insight into the problems of integrating lasers
and pointer/tracker systems. It is interesting to note that
a detailed study of a similar system using a wave optics
code resulted in an additional beam expander ($M = 1.3$) being
placed in the optical train.

The simplified optical train model has been developed
using state-of-the-art knowledge of the contribution of each
element (windows, mirrors, etc.). It should be noted, how-
ever, that the model has not been verified using the more
detailed wave optics codes. Such comparisons would be use-
ful to not only verify, but also to improve, these simplified
models.

Section 3

CREATION OF SAICOM

One of the High Energy Laser (HEL) propagation codes commonly used by the laser systems analysts is the COMBO (or ATM) code developed by the Air Force Weapons Laboratory (Reference 11). ATM is the propagation model documented in Reference 11. COMBO is a code which combines ATM with the Air Force HEL weight and volume projections (Reference 12). COMBO also includes some additional features such as the ability to perform reverse calculations in which the user specifies a desired intensity and the code determines the range at which the intensity can be delivered (given the power) or the power required (given the range). The primary asset of COMBO (or ATM) is its ability to make variable altitude calculations, including propagation paths extending to or from space.

One of the tasks performed under the present contract was devoted to modifying COMBO. The objectives were to reduce execution time, improve computational accuracy and to incorporate several of the newer developments resulting from the other tasks of this contract. A number of other minor additions, corrections and deletions were also made.

All of the primary modifications are discussed in Section 3.1. Collectively, they are sufficient to warrant a new code name -- SAICOM. A brief user's guide to SAICOM is provided by Section 3.2.

3.1   MODIFICATIONS OF COMBO

The primary modifications are dealt with in individual subsections below. The basic structure and organization

of the code remain essentially the same as in the original
version (Reference 11). A summary of the more important
equations is given in Section 3.1.9.

3.1.1 Improvements to Computational Speed and Accuracy

A substantial part of the COMBO modification effort
was devoted to improving the speed of the calculations.
Several modifications simply involved improvements in coding
techniques. These included: (1) reducing the number of
calls to MEGAIR (the subroutine which provides altitude de-
pendent parameters such as temperature, pressure, etc.);
(2) lumping several blooming parameters (viz., n, $\partial n/\partial T$,
and C_p) into a single curvefit (GALTIN); (3) using a better
search algorithm in the reverse calculations; and (4) reduc-
ing the subroutine calls.

Most of the improvement in both speed and accuracy
was obtained by developing a completely new algorithm for
performing the double integration required to compute the
blooming parameter, NI. The expression for NI is of the
form

$$NI = C \int_0^L \frac{1}{r(z')} \int_0^{z'} G(z'')dz''dz'$$

where C is fixed for a given set of conditions (Reference
13). The integration paths are along the beam. In the
original code, the double integral was evaluated by assum-
ing the integrals to be constant between uniformly spaced
points along the beam. The evaluation was successively
repeated with reduced spacing until the results for consec-
utive evaluations agreed with 10 percent. This procedure

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was found to be inefficient and often inaccurate. This should be readily apparent from Figure 3.1, which shows the important elements of the integral for a particular case of a highly focused beam. Note that the value of NI is dominated by the conditions within the last few percent of the range.

The new algorithm examines the local behavior of the integrand and chooses an efficient scheme and mesh spacing dynamically. It selects either a locally quadratic or locally exponential representation of the integrand. If neither is satisfactory, it reduces the mesh spacing and tries again. On the other hand, if the local convergence exceeds the accuracy requirements, it increases the mesh size to increase speed. Both integrations as well as a third implicit in G are performed in a single loop.

When the new algorithm was used for the severe example illustrated in Figure 3.1, the calculation required 1.49 seconds; the original COMBO exceeded a time limit of 200 seconds without completing the calculation!

As mentioned earlier, an additional improvement in computation time was obtained by modifying the convergence algorithm used in the reverse propagation calculation where the range is successively adjusted to obtain a desired target plane intensity. The range R' for one iteration is determined by modifying the previous range, R, viz.,

$$R' = KR \sqrt{I/OI}$$

where OI and I are the desired and computed intensities, respectively. In the original COMBO, the constant K was always 1.0, whereas in SAICOM, it varies between 0.7 and 1.0 to accelerate convergence. In addition, the convergence criterion was relaxed from 1% to 5%.
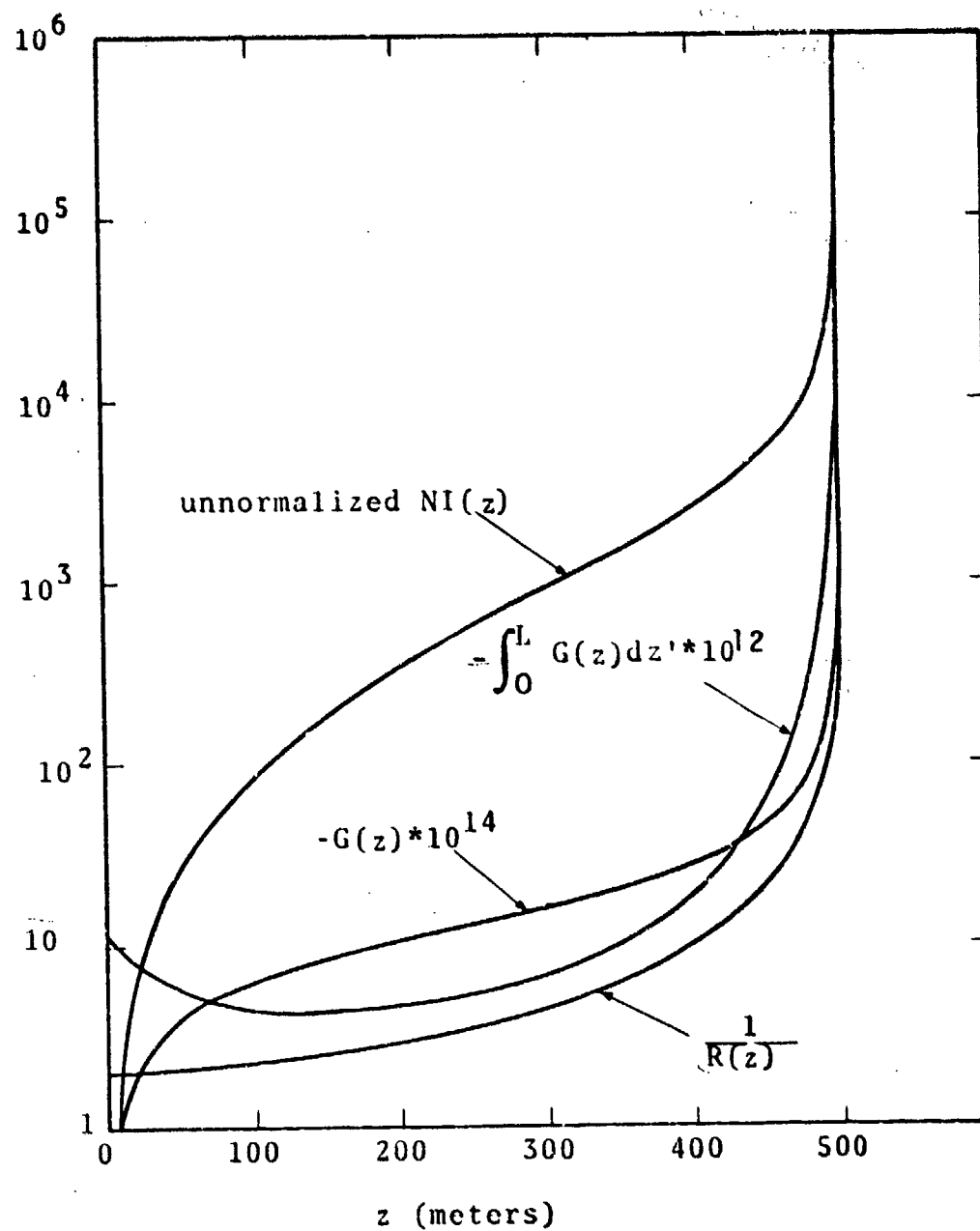
Figure 3.1   Variations in Elements of
              the Blooming Calculation

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3.1.2 Beam Quality

The SAICOM code includes a significant innovation in the treatment of beam quality. It essentially replaces the usual one parameter concept of an "m x diffraction limited" beam by a two parameter representation. The two parameters, designated m_1 and m_2, are used to specify a gaussian representation of the focal plane intensity profile so as to approximate the actual integrated power distribution. The two parameter model is inherently capable of including effects leading both to beam spreading (m_2) and to power loss due to wide angle scattering (m_1).

The origin and interpretation of m_1 and m_2 are discussed in some detail in Reference 1 and in Section 4.3 of this report. Their use in characterizing the effects of beam truncation and obscuration is discussed in Reference 2. In general, they are calculated in the new optical train model which is an integral part of SAICOM (see Section 2).

SAICOM incorporates the two parameter approach even though the user is only required to stipulate a single parameter, m. If the device power (P_D) and beam quality (m) are stipulated, the optical train portion of the code converts them to the appropriate aperture or transmitted power (P_T) and beam quality (m_1, and m_2). If the optical train calculations are bypassed because the user specifies P_T, the specified beam quality is assumed to be pure beamspread.

The SAICOM intensity expression for a focused beam is of the form

$$I = \frac{[1 - (1 - 0.865\, m_1\, z/L)]\, P_T e^{-\alpha z}}{\pi r^2(z)}$$

where

$$r^2(z) = \frac{D}{4L^2} |L - z|^2 + 4z^2 \left[\left(\frac{0.3183 \, m_2 \lambda}{D} \right)^2 \right.$$

$$\left. + \sigma_T^2 + \sigma_J^2 \right] .$$

The term in the numerator that decreases as z increases re-
presents the power losses that may be thought of as wide
angle scattering. The 0.865 factor is present because the
basic propagation equation used in the code is based on the
$1/e^2$ radiance of an infinite Gaussian beam. Since m_1 and m_2
are used to account for the effect of different beam pro-
files as well as phase perturbation, these terms may be not
the unity even for perfect beams. This situation is clari-
fied in Table 3.1. In this table the M1 and M2 terms are
the parameters computed in the optical train subroutine
while m is the user specified beam quality for the total
system. Note that if the optical train is bypassed (the
user specifies P_T) and m=1, m_1 and m_2 are 0.89 and 1.29
respectively for a uniform beam and not unity because the
basic propagation equation is based on an infinite gaussian
model. But if the optical train is not bypassed, m_1=
M1=0.89 and m_2=M2=1.29 because the basic profile used in
the optical train subroutine is uniform.

3.1.3   The Optical Train Model

The development of an improved optical train model
was the prime objective of Task 5 and is discussed in de-
tail in Section 2 of this report. The model has been in-
corporated into SAICOM as subroutine OPTRAIN. It computes
power losses, jitter, and beam quality degradation associ-
ated with transmission of the beam from the laser through

Table 3.1   Beam Quality Parameters

Aperture	Intensity Profile	Infinite Gaussian	$1/e^2$ Gaussian	Uniform
OPTRAIN BYPASSED	m_1	1	1	0.89
	m_2	1	1.41 m	1.29 m
OPTRAIN USED	m_1	0.89 M1	0.89 M1	M1
	m_2	0.775M2	1.092M2	M2

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the final t smitting optic. It accepts a quite general
specificati of the optical train through a list of input
parameters. OPTRAIN accounts for beam truncation and ob-
scuration and for various contributions to phase pertur-
bations. The output includes the two beam quality para-
meters m_1 and m_2 described above.

AIN can be bypassed simply by specifying the
transmitted power, P_T, rather than the device power in
the input. In this case, beam quality is based on wave-
length scaling as usual.

3.1.4 Multi-Line Propagation

Since many of the lasers of interest for high energy
applications emit several lines simultaneously, it is de-
sirable to include these multi-line characteristics in the
simplified propagation codes.

The approach used in SAICOM is to compute the amount
of energy absorbed by the air on a line-by-line basis. This
means that $\exp\left\{ -_0\int^R d(z''')dz''' \right\}$

$$\sum_i \frac{P_i}{P_T} \exp\left\{ -\int_0^R \alpha_i(z''')dz''' \right\}$$

and $\alpha(Z'')\exp\left\{ -\int_0^{Z''} \alpha(Z'')dZ'' \right\}$ in the integrand of the

expression for the blooming parameter becomes

$$\sum_i \frac{P_i}{P_T} \alpha_{ai}(Z'')\exp\left\{ -\int_0^{Z''} \alpha_{ei}(Z''')dZ''' \right\}$$

where

α_{ai} = absorption coefficient of the ith line

α_{ei} = extinction coefficient of the ith line.

In SAICOM, the 3.8 µm DF propagation has been extended to include three distinct families of lines. These encompass ten lines of the DF laser, and represent 80% of the output of the BDL device. With the basic modification having now been made, it is straightforward to include multi-line HF or CO propagation.

The derivation of the DF absorption coefficients is given in Appendix A and is based on the BDL spectral data. The resulting SAICOM equations are

$$\alpha_i = A_o e^{-A_1 + h(-A_2 + A_3 h)}$$

where $A_o = 1 + (0.9446\, RH - 1)e^{-h(6.738 \times 10^{-5} + 9.61 \times 10^{-9} h)}$,

for groups 1 and 2

= 1, for group 3

A_1 = 10.047, 10.082, and 9.948 for group 1, 2 and 3, respectively

A_2 = 6.388×10^{-4}, 6.952×10^{-4}, and 2.199×10^{-4}

A_3 = 2.25×10^{-8}, 1.55×10^{-8}, and -1.96×10^{-8}

h = altitude in meters.

These equations imply that at sea level α varies between 0 and 0.0409 km^{-1} as relative humidity varies between 0 and 100%, α_2 between 0 and 0.0395 km^{-1}, and α_3 is a constant 0.0478 km^{-1}.

The above equations are only valid to around h=13 km; for the higher altitude the original COMBO coefficients are used. Unfortunately, a discontinuity existed at the 13 km altitude; so transition equations were created to connect the multi-line data below 13 km with the single-line data above that point. Figures 3.2, 3.3, 3.4, and 3.5 plot the α_1, α_2, α_3, and $\alpha_{resultant}$ equations where

$$\alpha_{resultant} = \frac{\alpha_1 + \alpha_2 + \alpha_3}{3}$$

The scattering equations are the same as those used in the original COMBO (Reference 1i).

3.1.5   Modification of Turbulence and Jitter
         to Include Short and Long Term Effects

During the code comparison work in Task 1 of this contract, it was noted that one of the useful features of ESP was the flexibility of including beam jitter in the blooming calculation if the frequency were high enough and excluding it otherwise (References 1 and 14). This feature has been included in SAICOM. The output jitter factors in SAICOM are high-frequency jitter (σ_{JHF}) and low-frequency jitter (σ_{JLF}). The former is used in the calculation of the blooming parameter and both are combined to give the total beamspread due to jitter. Similarly, the turbulence calculations are expanded to include the total, long-term turbulence (σ_{TLT}) and the high-frequency, short-term turbulence (σ_{TST}). The turbulence equations in SAICOM are based on work of Yura (References 15 and 16) whereas the COMBO code was based on Fried's work (Reference 17), but the results differ only slightly in the regions of interest. The equations used are
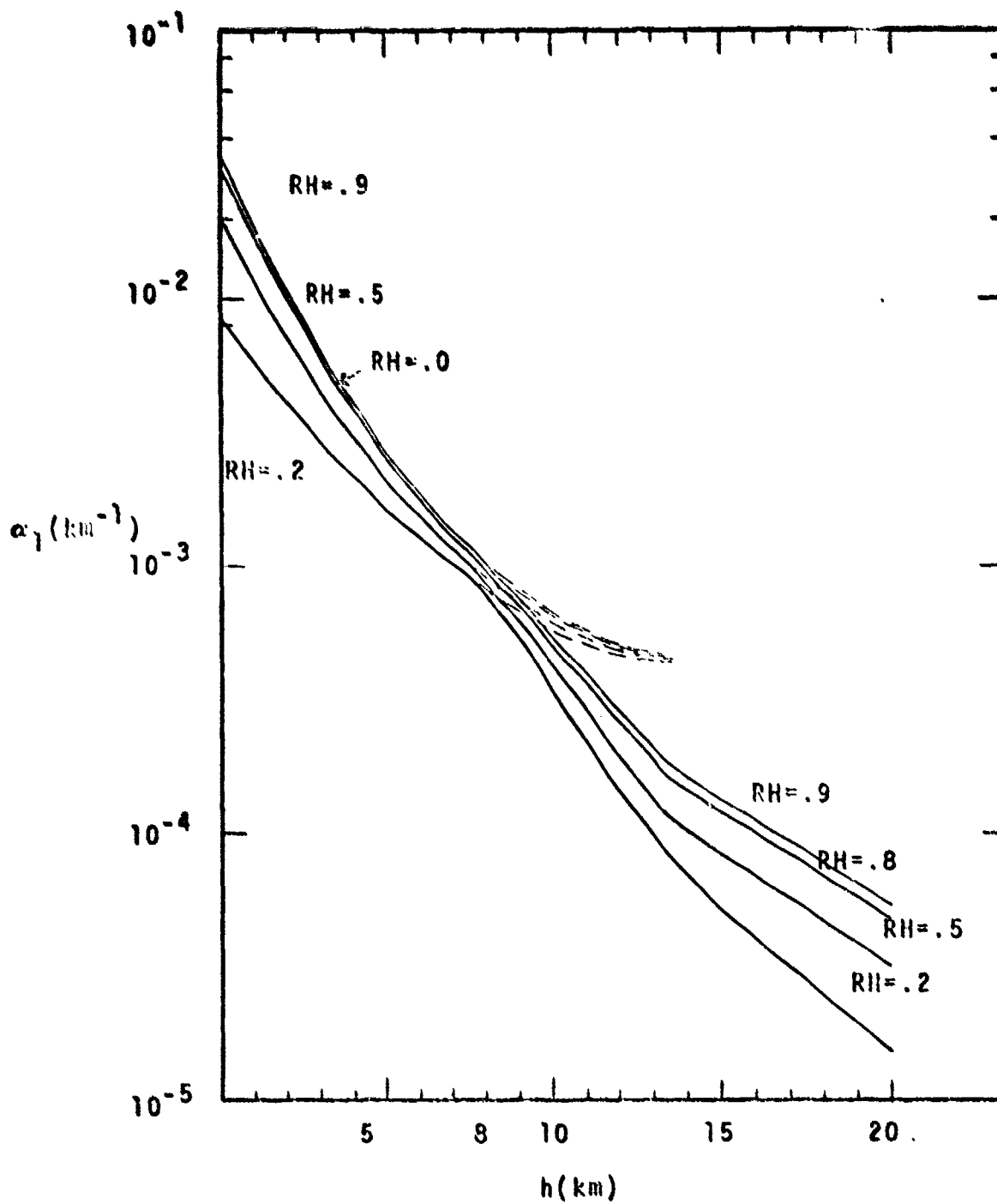
Figure 3.2. α_1 as a Function of Altitude
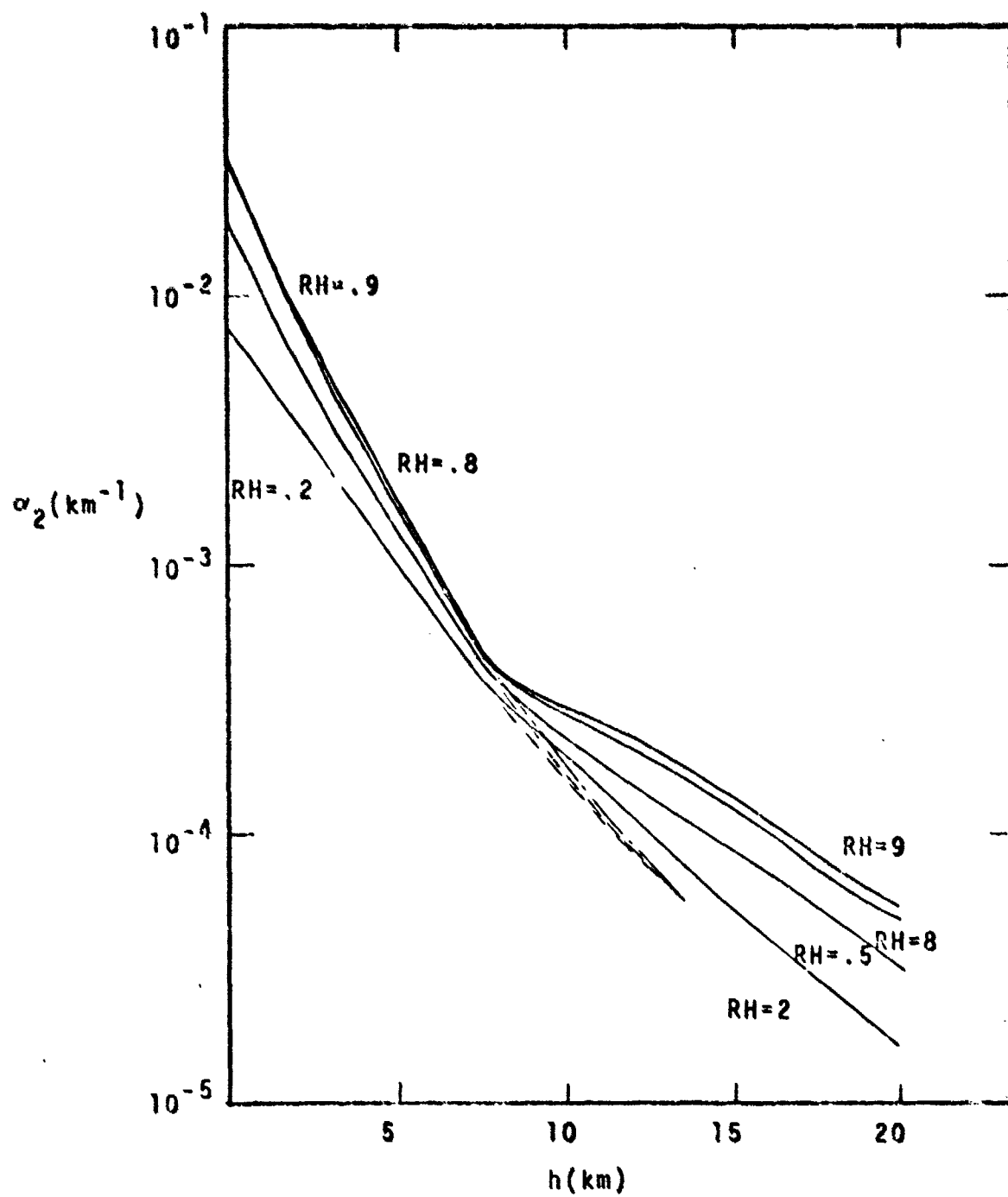
Figure 3.3. α_2 as a Function of Altitude
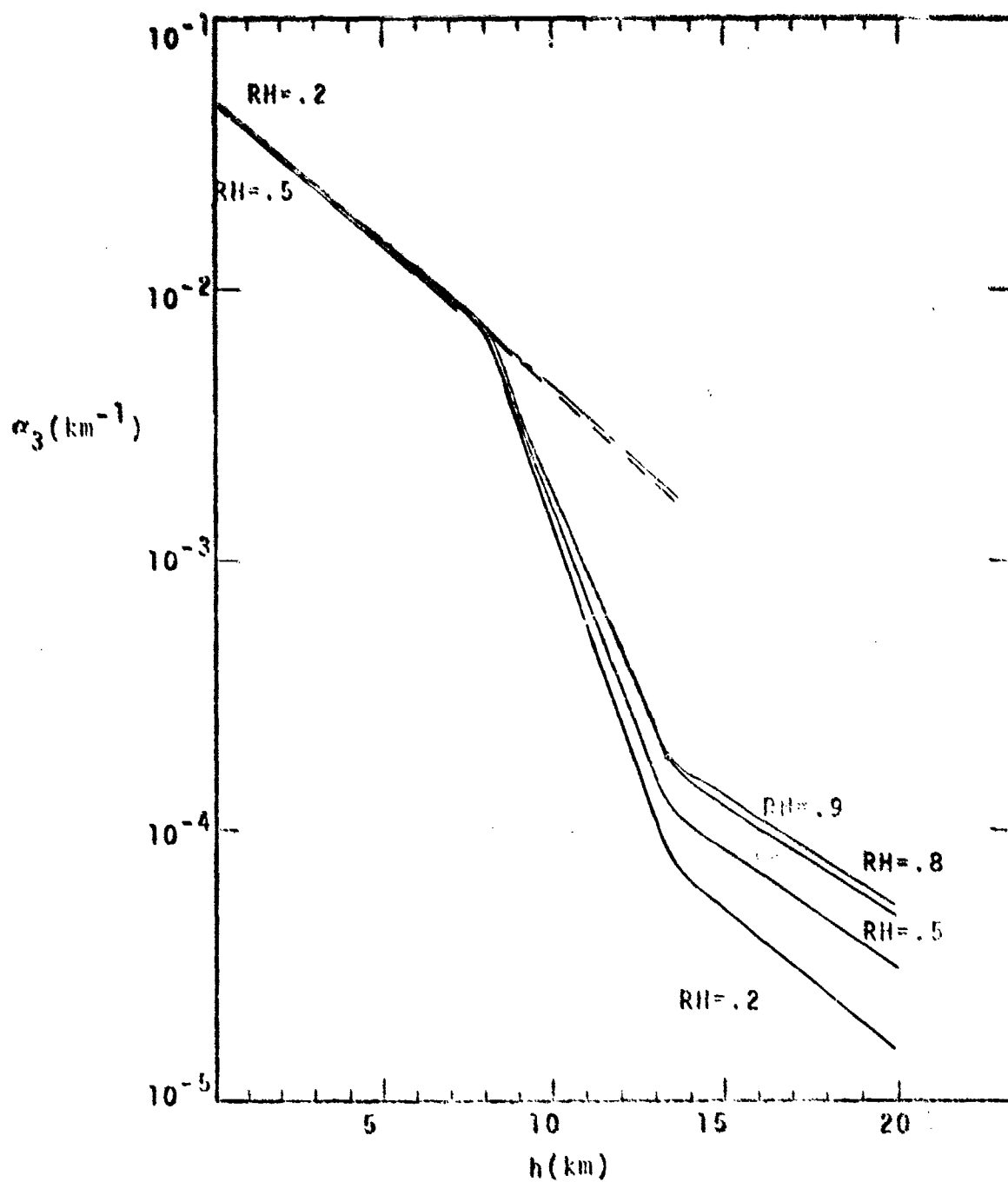
Figure 3.4. α_3 as a Function of Altitude
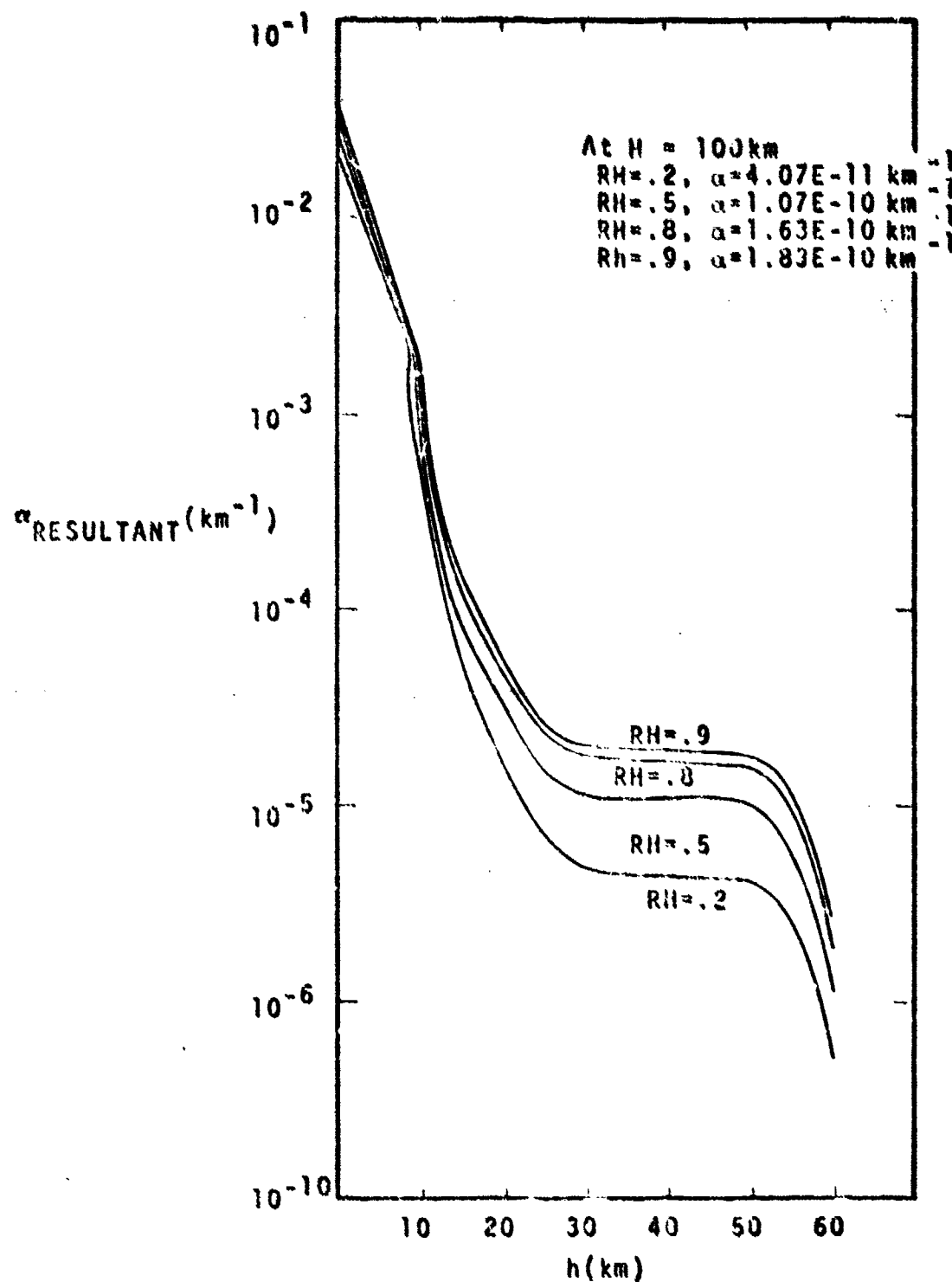
Figure 3.5. $\alpha_{RESULTANT}$ as a Function of Altitude

$$\sigma_{TLT} = \frac{2.549}{\lambda^{1.175}} \left[\int_0^L c_N^2 (z) \left(\frac{L-z}{L}\right)^{5/3} dz \right]^{3/5}$$

and
$$\sigma_{TST} = \left[1 - 0.37 \left(\frac{\rho_0}{D}\right)^{1/3} \right] \sigma_{TLT}$$

where
$$\rho_0 = \frac{1.439}{k^{1.2}} \left[\int_0^L c_N^2 (z) dz \right]^{3/5}$$

$k = 2\pi/\lambda$

D = diameter of the exit aperture.

These equations are generalizations of the co-altitude expression developed in Reference 16. In the blooming calculation σ_{TST} is used instead of the long-term expression, but it should be noted that some research indicates that no turbulence should be included in the beamspread before the blooming calculation (Reference 18).

3.1.6   Far-Field Intensity Distribution

In COMBO the standard calculation of the average intensity is based on the $1/e^2$ intensity radius in the far-field with a few other radii available for user specification (e.g., $1/e$ and $1/2$ intensity points). Since SAICOM is based on a gaussian approximation to the actual far-field distribution, it is a simple matter to use the $1/e^2$ results to describe the complete far-field profile. In addition to $I(1/e^2)$, the peak intensity $I_p = 2.312 \times I(1/e^2)$, is printed along with contour data. These contour data assume a

bivariant normal profile of the beam due to blooming distortion as developed in Reference 2. For each 10% contour ($I=\gamma I_p$, $\gamma=0.9, 0.8, \ldots, 0.1$) the area within that contour,

$$A(I>\gamma I_p) = \frac{\pi r^2 \ln(1/\gamma)}{2 \text{ KIP}}$$

the total power within that area,

$$P(I>I_p) = P(1-\gamma)$$

and the corresponding average intensity are printed. In addition, the beam displacement due to non-linear bending into the wind and the eccentricity of the resulting eliptical profile are computed and printed.

3.1.7 Calculation of Optimum Power

One of the more useful bits of information that comes from laser effectiveness studies is specification of optimum power based on maximizing energy on the target (Reference 19). Using the Gebhardt and Smith curve-fit for the intensity reduction due to blooming (Reference 20), the far-field intensity is related to transmitted power, P_T, by

$$I = aP_T \; I_{REL}(N)$$

where $N=bP_T$ and a and b are constants (independent of power). Setting $\partial I/\partial P_T=0$ leads to

$$\partial \ln(I_{REL}) = -\partial \ln N$$

as the optimum condition. For the Gebhardt and Smith curve,

this condition is satisfied when N=5.54. Therefore, the
optimum power is given by

$$P_{optimum} = \frac{5.54 P_T}{N}$$

where N is the value of the blooming parameter corresponding
to the power P_T. The corresponding maximum intensity is

$$I_{optimum} = \frac{1.205 I}{N \, KIP}$$

(KIP is the computer variable representing I_{REL}). It should
be noted that the optimization does not include the possible
effects associated with the optical train, i.e., it does
not involve an iterative recall of OPTRAIN.

SAICOM prints the optimum power as derived above
unless the corresponding intensity exceeds the air breakdown
threshold. In that case, it prints the power at which break-
down would occur as the optimum power. The breakdown power
level is estimated on the basis of peak intensity without
blooming.

3.1.8   Miscellaneous Modifications

Several relatively minor additions, deletions and
corrections are described below.

3.1.8.1 <u>Variable Turbulence in Blooming Computations</u>

In COMBO the turbulence is not varied as the bloom-
ing along the beampath is computed; instead only the final
value is used. In SAICOM the distributive nature of tur-
bulence is included in the integral calculation of the
blooming parameter.

3.1.8.2 Extinction Calculations in Blooming Integral

In COMBO the linear power losses due to absorption and scattering are computed using $\exp[-\alpha_e(h)z]$ in the integrand whereas the expression should have been

$$\exp\left[-\int_0^z \alpha_e(h)dz\right].$$

This error causes an over-estimate of the extinction losses when firing downward and an under-estimate when firing upward. The appropriate correction has been made in SAICOM.

3.1.1.3 Power Variation

The reverse calculation option in COMBO involving calculation of the required power to deliver a desired intensity at a given range has been replaced in SAICOM. Now, whenever the intensity is calculated in a normal propagation run, the power is automatically varied between one-tenth the specified value and twice the original power. The output then lists the average intensity within the $1/e^2$ intensity area, the area over which the intensity is above a specified minimum value, and the total power available within that area. The equations used in these computations were discussed in Section 3.1.6. The user is allowed to stipulate the minimum intensity of interest through the input parameter OI. If the user does not specify the desired minimum intensity contour, the program automatically selects 10 kw/cm^2.

3.1.8.4 Deletion of Weight and Volume Calculations

The technology projection portion of COMBO is an interesting but seldom used facet of the code. Therefore, it has been eliminated.

3.1.9   Summary of Equations

The basic equations used in SAICOM are as follows:

Average intensity in the $1/e^2$ intensity radius

$$I(Z) = \frac{\left[1-(1-0.865\, m_1\frac{z}{L})\right]\, P_T\, k_B\, e^{-\sum_i \int_0^Z \alpha_{ci}(Z')dZ'}}{\pi r^2(Z)}$$

where k_B = intensity reduction due to blooming
(sometimes written as KIP)

$\qquad\quad = f(N)$

$$r^2(Z) = k_2 r_0^2 + k_3\frac{r_0^2}{L^2}\, |L-Z|^2 + 4Z^2\left[\left(\frac{0.3183 m_2\lambda}{D}\right)^2\right.$$

$$\left. + \sigma_{TLT}^2 + \sigma_J^2\right]$$

$$\sigma_J^2 = \sigma_{JHF}^2 + \sigma_{JLF}^2$$

$$\sigma_{TLT} = \frac{2.549}{\lambda^{1/5}}\left[\int_0^L C_N^2\,(Z)\left(\frac{L-Z}{L}\right)^{5/3}dZ\right]^{3/5}$$

The blooming parameter, N, is computed by

$$N = \frac{6.54}{\pi}\int_0^L \frac{1}{r(Z')}\int_0^{Z'}\frac{\left[1-(1.865 m_1\frac{Z}{L}\right]\, F(Z'')G(Z'')dZ''dZ}{v(Z'')r^2(Z'')}$$

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where

$$F(Z'') = P_T \sum_i \frac{P_i}{P_T} \, \alpha_{Ai}(Z'') e^{-\int_0^{Z''} \alpha_{ei}(Z'') dZ''}$$

$$r^2(Z'') = k_2 r_0^2 + k_3 \frac{r_0^2}{L^2} |L-Z|^2 + 4Z^2 \left[\left(\frac{0.318 m_2 \lambda}{D} \right)^2 + \sigma_{TST}^2 + \sigma_{JHF}^2 \right]$$

$$\sigma_{TST} = \left[1 - 0.37 \left(\frac{\ell_0}{D} \right)^{1/3} \right] \sigma_{TLT}$$

$$\ell_0 = \frac{1.439}{k^{1.2}} \left[\int_0^L C_N^2(Z) dz \right]^{3/5}$$

$$k = 2\pi/\lambda$$

$$G(Z'') = \frac{\frac{\partial n}{\partial T}(Z'')}{n(Z'') \rho(Z'') C_p(Z'')}$$

3.2 A USER'S GUIDE TO SAICOM

A brief description of the key features of the
SAICOM code is given along with a discussion of how to
operate the code. Users familiar with COMBO (Reference 11)
should have little trouble with SAICOM since many of the
subroutines are unchanged and the same modular format has

been retained. The basic structure of the executive routine
(SAICOM) is shown in Figure 3.6. A substantial portion of
this routine is devoted to initializing the input variables.
As with COMBO, most of the input parameters are defined
through a default namelist which requires the user to specify
only those parameters which will differ from the default
values. However, it should be noted that even if the propa-
gation and optical train namelists are not used, namelist
cards are required which read $INPUT $ and $CASES $, respec-
tively. The optical train is called if the user specified
PD; if PT is given, this subroutine is bypassed. A subtle
point worthy of note is that when PD is given, SIGHF is
assumed to refer to the device jitter only, and this term
is combined with the four 1σ jitters (THIR, THES, THAA, and
THSV) given in namelist CASE to determine the high-frequency
jitter of the total system.

Iterate for NRUNS
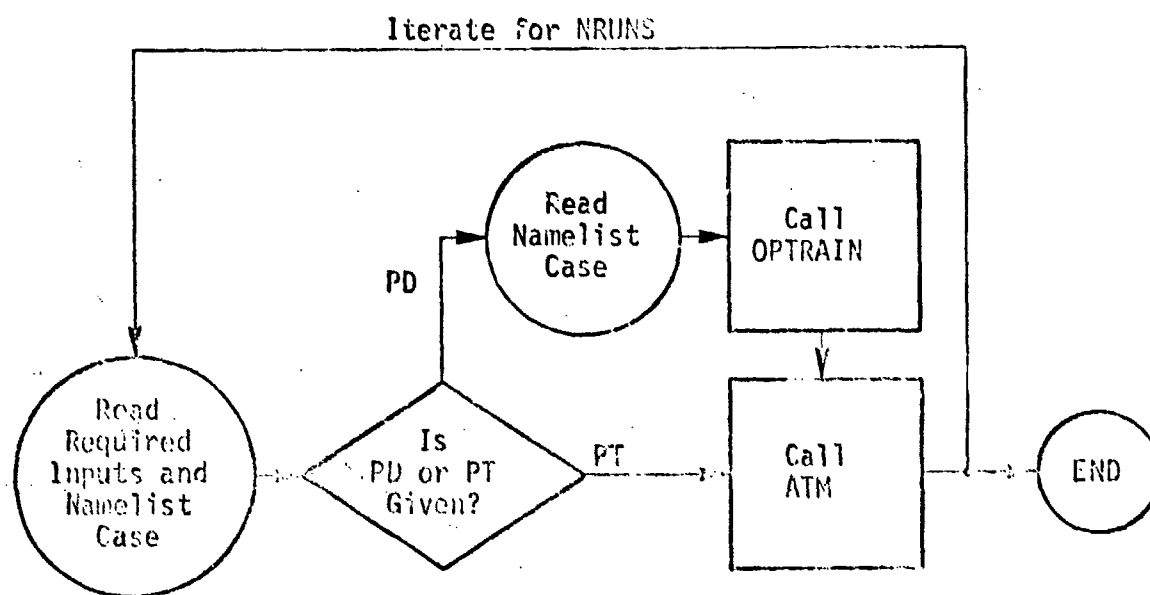
Figure 3.6   SAICOM Flow Diagram

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Following these initialization activities, control is transferred to ATM, which handles the propagation calculations; control returns to SAICOM only after the calculations are completed and the results printed. Then SAICOM cycles through the same process until all of the specified cases have been completed.

In Table 3.2 a complete list of the SAICOM subroutines is given along with brief descriptions of their functions. Three of the subroutines, OPTRAIN, ATM, and BB, are discussed in further detail since they are the more important and complex portions of the program.

3.2.1 OPTRAIN

The calculation procedure within the Optical Train Model (OPTRAIN) is schematically shown in Figure 3.7. All inputs to the subroutine are passed through a labeled COMMON/OPTIN/statement and must be defined by the user prior to calling the subroutine. Following some initial calculations characterizing the input beam, the effect that each component within the optical train has on the transmitted power and beam quality is evaluated in a step by step manner. Although the specific elements within the optical train are fixed, i.e., aerodynamic window, beam clipper, mirrors, beam expander, and exit aperture, the user is allowed to specify, through the input parameters, different types of individual components such as cooled or uncooled mirrors, on-axis or off-axis beam expanders, and open port or material window exit apertures.

The output from the model is returned to the calling program via the labeled COMMON/OPTOUT/ and consists of (1) the diameter of the laser beam at the exit aperture, (2) the power in the beam, (3) the total beam jitter and (4)

Table 3.2   SAICOM Subroutines

NAME	DESCRIPTION
OPTRAIN	Calculation of Power Loss and Beam Degradations in the Optical Train.
ATM	Initialization of Propagation Parameters and Iteration of Reverse Calculations.
AA	Calculations for Laser and Target Above 100 km.
AB	Calculation for Laser Above 100 km and Target Below 100 km.
BA	Calculation for Laser Below 100 km and Target Above 100 km.
BB	Calculations for Laser and Target Below 100 km.
ALFSET	Sets Power Ratios for Multi-Line. Propagation.
ALFFAC	Calculations of $\alpha_A e^{-\alpha_e Z}$ and $e^{-\alpha_e Z}$.
ALFAAB	Single Line Absorption Coefficients.
ALFAEX	Single Line Scattering Calculation.
CNSQ	Atmospheric Structure Constant.
KI	Computer Reduction in Intensity Due to Blooming.
GALTIN	Altitude Dependent Parameters Used in Blooming Integral.
MEGAIR	Pressure, Density and Temperature as a Function of Altitude.
VX	Calculation of Total Crosswind.
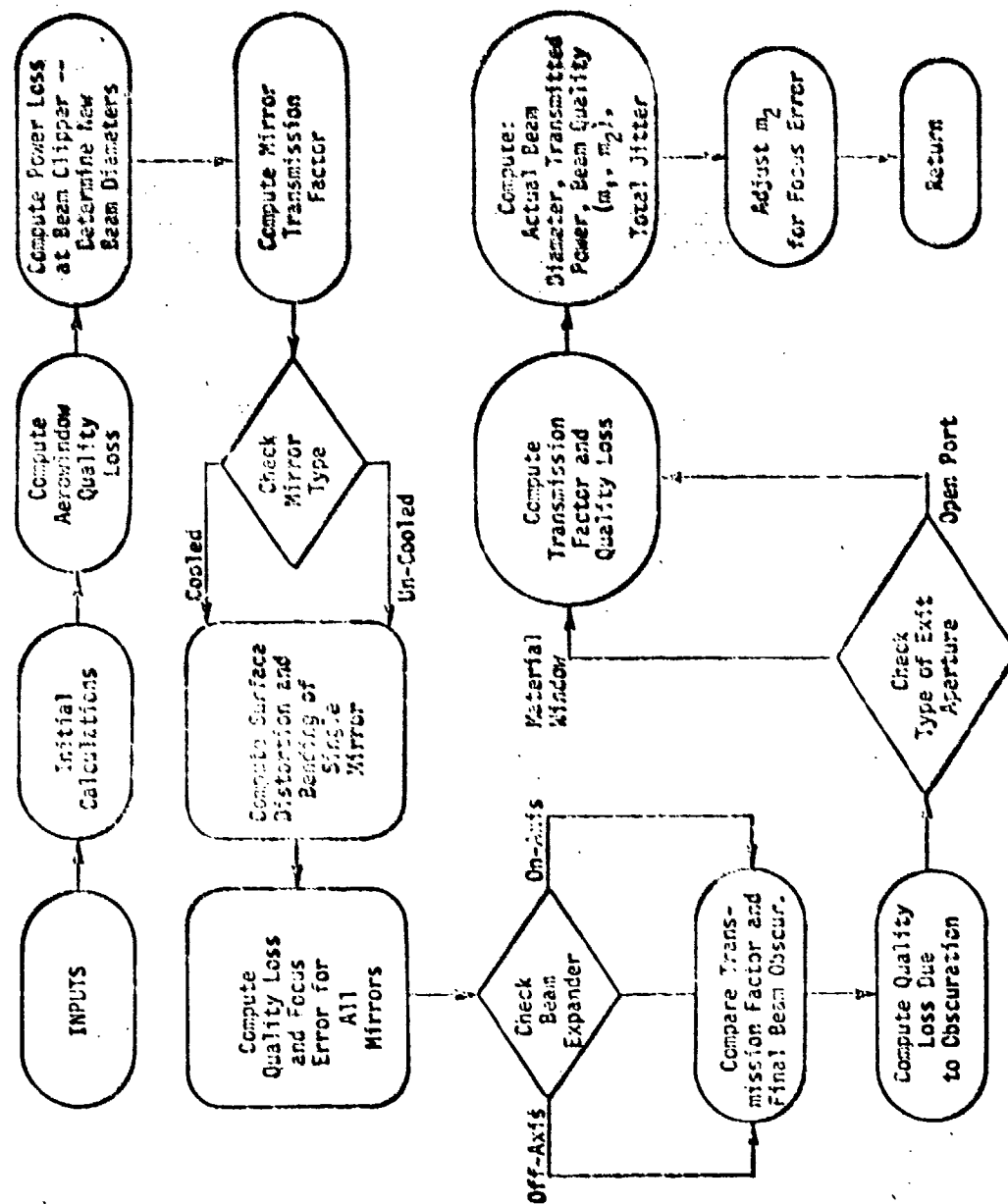
Figure 3.7 OPTRAIN Flow Diagram

two parameters (m_1 and m_2) characterizing the optical quality
of the beam. The beam quality parameter m_2 is internally
adjusted to account for any defocusing error induced by the
high power mirrors in the optical train.

3.2.2   ATM

Part of the initialization process in ATM is to
determine if the user has specified a negative wavelength
(e.g., -1.06E-5 or -3.8E-6) which means the user is speci-
fying his own single line absorption and scattering
coefficients

$$\alpha_A = ABL * EXP (-ABC * R)$$

$$\alpha_S = SCL * EXP (-SCE * R)$$

or his own power ratios for the multi-line 3.8 µm propaga-
tion (see Figure 3.8). Note that single-line 3.8 µm propa-
gation is available only if the user specifies his own co-
efficients. Also note that if one wishes to alter the
power ratio, PLINE(I), $I = 1, 2, 3$ without altering the
built-in multi-line coefficients, simply set LAMDA equal
to -3.8E-6 and leave the absorption and scattering coeffici-
ents off namelist USPEC. The three power ratios need not
total unity since the program is self-normalizing. The
heart of ATM is the call to AA, AB, BA, or BB where the
intensities for the pathlengths of interest are calculated.
If AB or BA are called, they in turn call BB for those
portions of the propagation path that lie below 100 km.
Following the return to ATM, the beam displacement, eccen-
tricity, contour data, breakdown power, optimum power, and
effects of power variations are determined for straight
propagation unless the propagation path is totally exo-
atmospheric (AA), or the blooming parameter NI is less
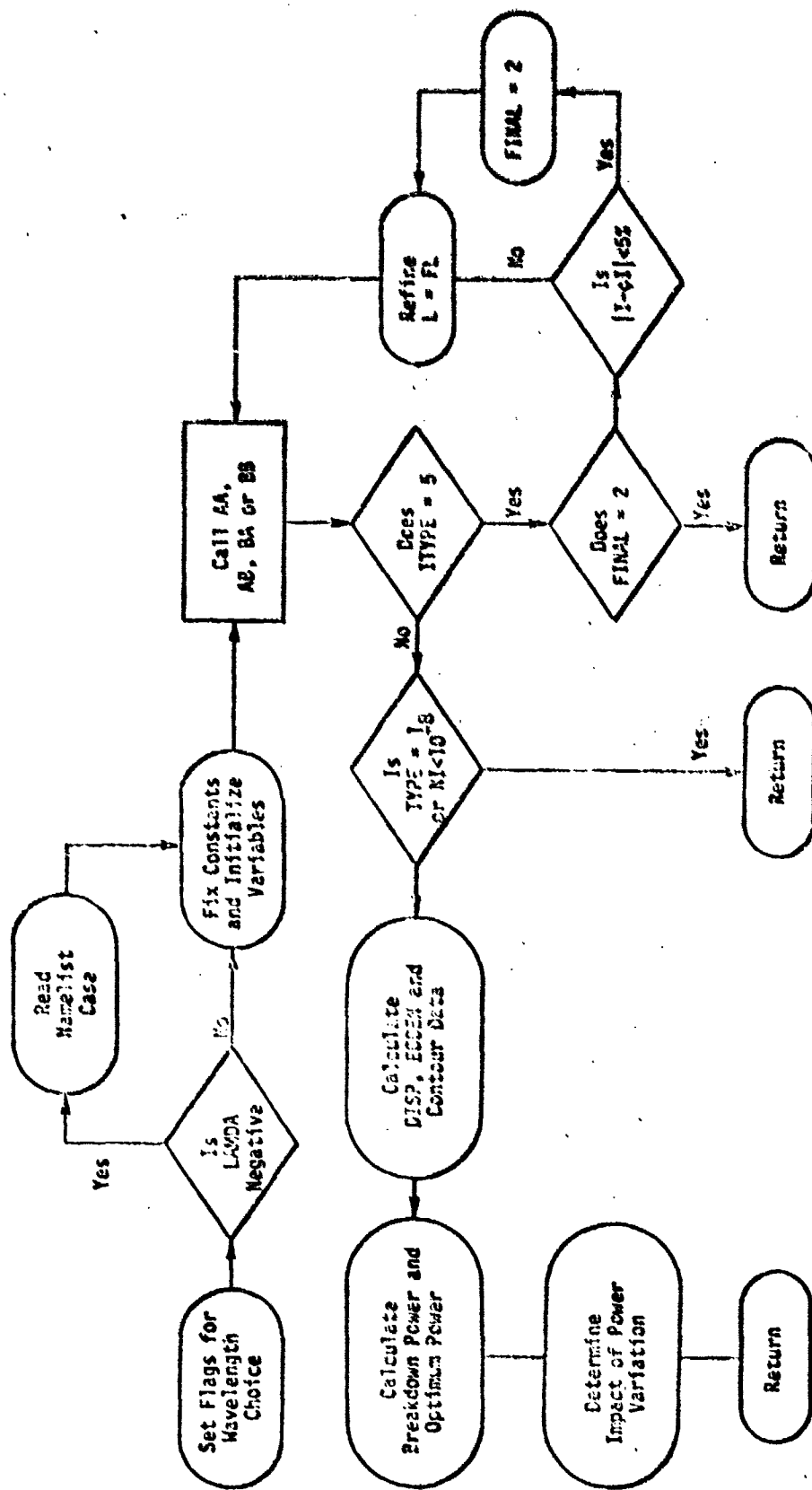
Figure 3.8 ATM Flow Diagram

than 10^{-8}. It should be noted that when the power is varied to compute the impact of propagating a beam that is more or less powerful than the specified level, the beam quality is not altered; this gives some error to the results since beam quality is affected by the total power transmitted through the optical train.

If the reverse propagation option (ITYPE = 5) has been chosen, the calculations are repeated using different target ranges (= focal ranges for ITYPE = 5) until the calculated intensity is within 5% of the desired value. If convergence is not achieved within 20 iterations, the program returns control to SAICOM and goes to the next case.

3.2.3   BB

In Figure 3.9, the logic flow for the BB subroutine is shown. all cases except AA use this subroutine to compute the atmospheric effects on the high-power beam propagation. The subroutine performs calculations at discrete points along the beampath. For calculations of the linear propagation effects, the pathlength intervals are fixed (NSTEP = 30 is the default value) while in the blooming loop the intervals are increased or decreased as required to minimize time and increase accuracy of the calculation. A series of linear or exponential extrapolations for the ith interval based on the ith - 1 interval are made and compared with the actual calculation for the ith interval. If the comparison is unfavorable, the interval is decreased. If the comparison is favorable, the contribution from the interval is incorporated into the integral, if the comparison is unnecessarily good, the interval is increased. This procedure replaces the time-consuming multiple interations used in COMBO.

3.2.4   Input Data

In Table 3.3 a list of the input parameters and their functions is given. This reference list does not
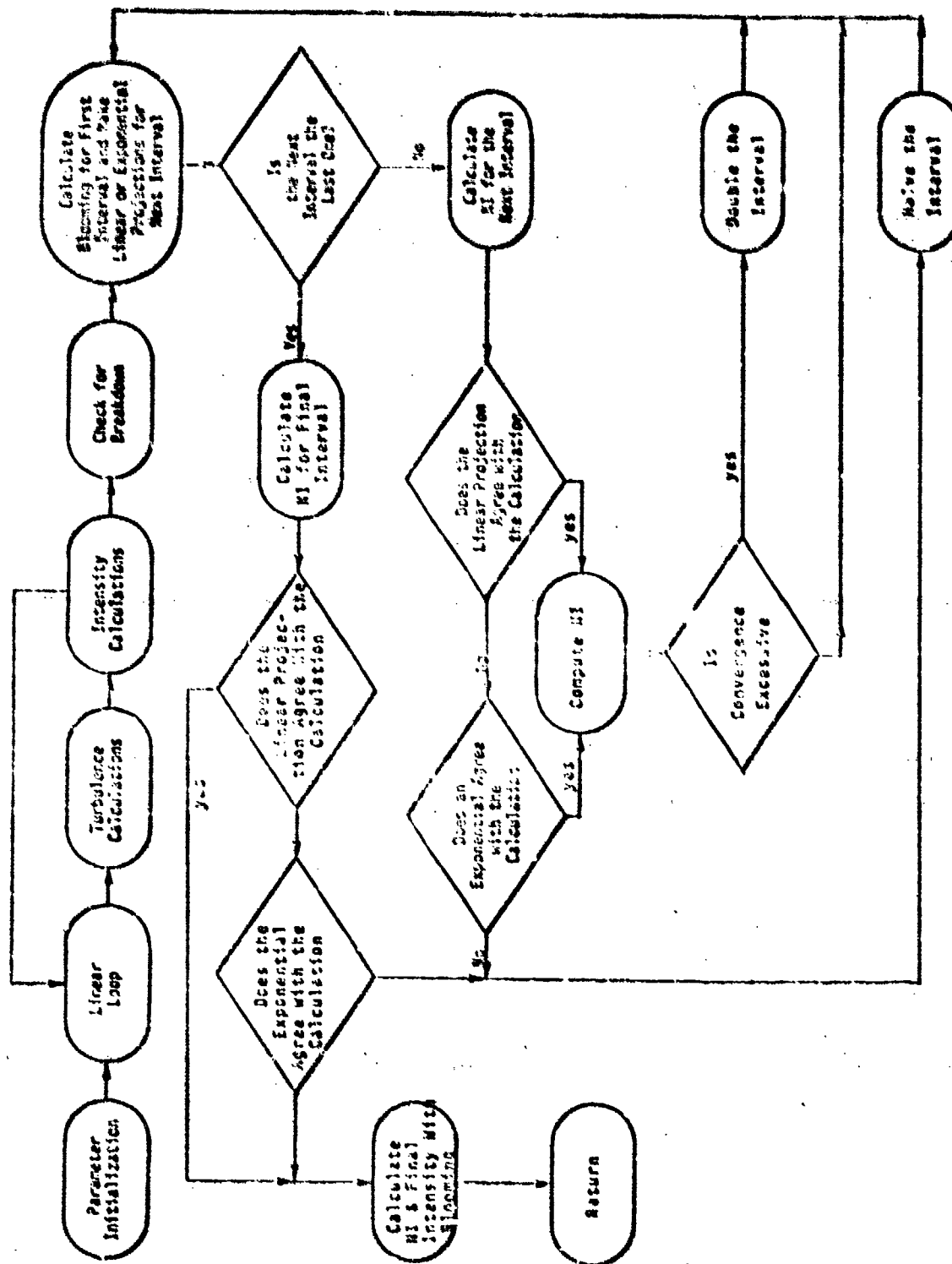
Figure 3.9. EB Flow Diagram

Table 3.3   Input Parameters

ITYPE

If ITYPE = 5 reverse calculation is called with OI and PD or PT specific. All other entries will result in straight propagation.

PD or PT

User may stipulate either device power or telescope power; if PT is specified OPTIMIZE is bypassed.

OI

Desired intensity of ITYPE = 5; otherwise it is the minimum intensity contour in the variable power calculation.

L

Range from laser to the target if ITYPE ≠ 5; if ITYPE = 5, L is a first guess for the range.

OPTIONAL - NAMELIST/INPUT/

Beam

0 ⇒ Collimated, 1 ⇒ Focused.

CHI

Horizontal projection of beampath with respect to the direction of platform movement.

DEBUG

1 ⇒ no extra diagnostic statement, 2 ⇒ extra diagnostic statement.

FL

Focal length.

GL

Ground level.

HTM

Target altitude.

HOM

Laser altitude.

Table 3.3 (Continued)

<u>OPTIONAL - NAMELIST/ INPUT/ (Continued)</u>

LAMDA   Wavelength

3.8×10^{-6}, 5.0×10^{-6}, and 1.06×10^{-5} are
the acceptable values. A negative sign
in front is a flag that the user will
specify the multi-line power ratios or
the single line absorption and scatter-
ing coefficients.

M   Beam quality.

NSTEP   Beampath intervals in the linear calcu-
lation.

OMEGA   Slewing rate.

OUT   1 $\Rightarrow$ standard output, 2 $\Rightarrow$ extra output.

PHI   Firing angle with respect to zenith.
If PHI is specified HIM should not be
given and vice versa.

PROP   1 $\Rightarrow 1/e^2$
2 $\Rightarrow$ plane wave, truncated Gaussian
3 $\Rightarrow$ infinite Gaussian.

RH   Relative humidity.

RI   Radius of obscuration.

RO   Outer radius of exit aperture.

SIGHF   High-frequency turbulence.

VP   Platform velocity.

VXP   Total crosswind across beam. If it is
specified VP, OMEGA and natural wind
are inoperative.

WTHR   -1 $\Rightarrow$ high turbulence, low natural wind
0 $\Rightarrow$ nominal turbulence and natural wind
1 $\Rightarrow$ low turbulence, high natural wind.

Table 3.3 (Continued)

OPTIONAL - NAMELIST/CASE/

DB	Beam diameter coming from the laser.
EPS	Obscuration ratio.
DL	Pulse length.
XRI	Phase front curvature.
DIOVI	Peak-to-peak intensity fluctuation.
DLI	Scale size of fluctuation wrt beam size.
DELTAR	Aerowindow.
RREF	Aerowindow density divided by ambient density.
XLC	Distance from laser exit to beam clipper.
DC	Clipper diameter.
N	Number of mirrors in optical train.
REFL	Reflectivity of each mirror.
SFAB	Mirror fabrication error.
ITYPE!	Mirror type: 1 ⇒ cooled, 2 ⇒ uncooled.
XLMIR	Distance between mirrors.
XMAG	Telescope magnification.
ITYPEB	Telescope type: 1 ⇒ on-axis, 2 ⇒ off-axis.
XLEA	Exit aperture width.
BETA	Exit aperture absorption coefficient.
ASAB	Strut area/beam area.
ITYPEA	Type of exit aperture: 1 ⇒ material window, 2 ⇒ open port.

Table 3.3 (Continued)

OPTIONAL - NAMELIST/CASE (Continued)

THTR	Tracker jitter (1σ).
THBS	Boresight jitter (1σ).
THAA	Autoalignment jitter (1σ).
THSV	Servo jitter (1σ).

OPTIONAL - NAMELIST/USPEC

PLINE (1)	Percent (or actual) power in line 1.
PLINE (2)	Percent (or actual) power in line 2.
PLINE (3)	Percent (or actual) power in line 3.
ABL	User specified linear absorption coefficient.
ABE	User specified exponential absorption coefficient.
SCL	User specified linear scattering coefficient.
SCE	User specified exponential scattering coefficient.

include the first two cards which must precede each set of
runs. The first uses I2 format in columns 1 and 2 to state
the number of cases (NRUN) which will be run, the second
uses free-field format to allow the user to title each of
the runs. The first card appears only once while the
title card must precede each new case. Hence, the data
stream is as follows:

```
NRUN CARD
Title
Required Inputs
Namelist INPUT                    Case 1
Namelist CASE
Namelist USPEC (if required)


Title
Required Inputs
Namelist INPUT                    Case 2
Namelist CASE
Namelist USPEC (if required)
```

Table 3.4 provides a convenient work sheet format
that may be used to specify each case. It includes a list
of the default values and units. Those familiar with COMBO
will recognize a change in some of the default values; the
default statements now reflect sea level applications.
Note that either PHI or HTM may be specified, but that PHI
should always be given as a positive angle (measured from
the zenith). A negative PHI is a flag that HTM was specified.

For additional convenience, Table 3.5 lists several
of the important program flags which may be of interest to
the user. A complete program listing and sample run is supplied
along with a sample problem output in Appendix B.

Table 3.4   Sample Input Form with Default Values

Required	Type	Position	Units	Case 1	Case 2	Case 3
TTYPE ✓	(3,5)	I2				
PD^2 or	(3,5)	11-20	W			
PT	(3,5)	21-30	W			
OI^5	(3,5)	31-40	w/m^2			
L	(3)	41-50	m			

Namelist "INPUT" Optional	Default		Units	Case 1	Case 2	Case 3
BEAM ✓	1 (focused)					
CHI	0.52		rad			
FL	L		m			
GL	0.		m			
HOM	50.		m			
HTN	10.		m			
LAMDA	3.8E-6		m			
M	1.5					
NSTEP ✓	30					
OMEGA	0.		rad/sec			
OUT ✓	1 (short)					
PHI^3	-1.E-6		rad			
PROP ✓	1 (Gaussian)					
RH	0.5					
RI	.08		m			
RO	.35		m			
SIGHF	5.E-6					
SIGLF	5.E-6					
VP	15.		m/sec			
VXB	0.		m/sec			
NTHR ✓	0 (normal)					

Table 3.4 (Continued)

Namelist "CASE" Optional[1]	Default	Units	Case 1	Case 2	Case 3
ASAB	0.05				
BETA	0.01	m^{-1}			
DD	.16	m			
DC	0.166	m			
DELT	1.0	°K			
DELTAR	0.1				
DIOVI	0.5				
DLI	0.1	L/WT			
DT	2.0	seconds			
EPS	.36				
ITYPAW ✓	1 (focused)				
ITYPEA ✓	2 (open)				
ITYPEB ✓	1 (on-axis)				
ITYPEM ✓	1 (cooled)				
N ✓	5				
REFL	0.985				
RI	1.670	m			
RRLE	2.5				
STAB	1./8.	vis lamda			
THAA	5.E-6	rad			
THBS	5.E-6	rad			
THSV	5.E-6	rad			
THTR	5.E-6	rad			
XLC	50.	m			
XLEA	0.05	m			
XLMIR	.15	m			
XMAC	4.375				

Namelist "USPEC" Optional	Default	Units	Case 1	Case 2	Case 3
Pline (1)	.338				
Pline (2)	.32				
Pline (3)	.342				
ABE	0.	m^{-1}			
ABL	0.	m^{-1}			
SCE	0.	m^{-1}			
SCL	0.	m^{-1}			

NOTES:

1. Check mark (✓) indicates "I" format is required.
2. User may specify either power exiting the device or telescope.
3. PHI need not be specified if HTM is given.
4. Although data on $INPUT$ card are optional, the card must be present even when all default values are to be used. The same applies to data card $CASE$. The namelist card $USPEC$ is only read when a negative lamda has been inserted on data card $INPUT$ as a flag.
5. If ITYPE = 5, OI is the desired intensity for the reverse calculation; otherwise it is the minimum useful intensity for the variable power tabulation (default value of 10^7 w/m^2).

Table 3.5   Flags

FORM   MEANING

Inputs
Negative LAMDA   The users will specify the multi-line
                          power ratios or the single-line absorp-
                          tion and scattering coefficients.

Negative PHI   HTM is specified (Default).

Internal
CNVRGD   TRUE => the last blooming interval
                          passed over the end point.

ENDED   TRUE => this is the last blooming interval.

ERR   TRUE => the reverse calculations have not
                          converged in 20 iterations.

FINAL   = 1, the reverse calculations have not
                          converged yet;

                          = 2, last pass through the propagation
                          calculation.

FRACT   Tells the fraction of the last blooming
                          interval that is within L.

LAM   = 1, 10.6 μm
                          = 2, 3.8 μm (multi-line)
                          = 3, 5 μm (single-line at present)
                          = 4, user will specify single-line
                          absorption and scattering coefficients.

OK   TRUE => save previous values for multi-
                          line absorption and scattering calcula-
                          tions.

3-36

Table 3.5 (Continued)

FORM	MEANING

<u>Internal</u> (Continued)

TYPE = 1, AA
     = 2, BB
     = 3, AB
     = 4, BA.

UNIFRM   TRUE => last two blooming intervals were the same.

Section 4

SUMMARY OF TASKS I-IV

The purpose of this section is to briefly review
the objectives and results of the original four tasks.
Specific details may be found in the first and second
interim reports (References 1 and 2). The primary
objective here is to highlight some of the issues which
arose during the course of the work and to indicate some
of their implications as they relate to propagation
modeling in general.

4.1   REVIEW OF TASK I. CODE COMPARISONS

The objective of Task I was to quantitatively
compare the results obtained from three propagation
codes over a parameter space representative of realistic
engagement conditions. The codes were: NOLEC (Naval
Surface Weapons Center); COMBO (Air Force Weapons
Laboratory); ESP-I (United Aircraft Research Laboratories).
The comparisons were presented at the First DOD Conference
on High Energy Laser Technology on 3 October 1974 in
San Diego (Reference 14). An unclassified version of this
paper is included as an appendix in the first interim
report (Reference 1). The major conclusions from these
comparisons were that all three codes give comparable
results for situations in which thermal blooming is not
severe, but that ESP-I gives intensities up to an order of
magnitude or more higher than the other two codes when
blooming is significant. NOLEC and COMBO agree reasonably
well under most conditions.

A secondary objective of Task I was to ascertain the reasons for major discrepancies between the codes. The effort was concentrated on COMBO and ESP-I since there is considerable disparity in their results even though they both use essentially the same approach for calculating thermal blooming. NOLEC uses an entirely different approach. In reviewing the theoretical basis of the codes, several issues were raised whose significance goes beyond the immediate objectives of the present work.

The blooming subroutines in both COMBO and ESP-I are based on the theoretical and experimental work of Gebhardt and Smith (Reference 20). The essence of the basic approach is the representation of the ratio of the bloomed and unbloomed focal plane peak intensities, I_{REL}, as a function of a single "blooming parameter," N. N is a theoretically derived, dimensionless, similarity parameter. However, the relationship between I_{REL} and N was obtained experimentally. Both COMBO and ESP-I use the same empirical relationship for I_{REL} (N). They yield different results in blooming calculations because they compute N differently. The differences in the recipes for calculating N were identified explicity in the First Interim Report (Reference 1). The question as to which method is more "correct" could not be resolved on theoretical grounds for several reasons.

1. An approximation to the theoretically derived expression for N was used in correlating the experimental data. The approximation was not generally valid even for the conditions of the experiments. It is even more questionable for realistic engagement-scale conditions such as those for which the simplified propogation codes are used.

2. COMBO uses the theoretical expression for N except for a relatively minor _ad hoc_ correction. In principle, this has some important advantages, such as an inherent capability to treat non-coaltitude engagements. Unfortunately, it is not consistent with the empirical relationship used to correlate the experimental data.

3. ESP-I uses the same expression for N as was used for the empirical correlation. In that sense, it is at least consistent. However, it does not engender much confidence in the extrapolation from small scale laboratory experiments to realistic engagement conditions.

To summarize the situation, both COMBO and ESP-I use a semi-empirical blooming model which is flawed by a basic inconsistency between its theoretical and empirical components. The First Interim Report implies a preference for COMBO simply because it was in closer agreement with NOLEC. It should be emphasized, however, that this may be, at least to some extent, fortuitous. Furthermore, there does not exist sufficient data to provide convincing validation of any of the codes.

Evaluation of the codes on theoretical grounds in any kind of absolute sense was beyond the scope of the study, but two observations are in order. First, the consistency problem with the Gebhardt and Smith blooming model does not necessarily reflect adversely on its basic approach; the deficiencies are primarily associated with its implementation. Secondly, there are no clear and obvious theoretical reasons why either of the basic approaches should be superior in accuracy to the other. All of the codes incorporate numerous simplifying assumptions and approximations, both explicit and implied, and rely to some extent on heuristic arguments.

4.2   REVIEW OF TASK II. BEAM SHAPE AND DISPLACEMENT

The objective of this task was to develop empirical
models for predicting beam shape distortion and displacement
in the focal plane due to thermal lensing. Results from the
NRL non-linear propagation code were used as he data base
for the analysis.

Since beam distortion and displacement both are
closely related to thermal blooming, I_{REL} (the reduction
in peak intensity due to blooming) was used as the primary
correlation parameter. This automatically accounts for
much of the dependence on the independent parameters and
has the further advantage of being readily computed from
the NRL scaling law.

The beam displacement model is represented by

$$\left(\frac{d}{a_f}\right) \eta^{.29} = \frac{-0.519 + \sqrt{(0.519)^2 + 1.500 \ln (1/I_{REL})}}{0.750}$$

where d is the displacement of the peak intensity into the
wind, a_f is the e^{-1} beam radius (without blooming) in the
focal plane, a_i is the e^{-1} beam radius in the source plane,
and $\eta = a_f / a_i$.

The beam shape model represents the constant inten-
sity contours as ellipses and the intensity distribution
as

$$I(x,y) = I_{PEAK} \exp\left\{ -SD \left[\left(\frac{x}{a_f}\right)^2 + \left(\frac{y-d}{Da_f}\right)^2 \right] \right\}$$

where

$$D = 0.3 + 0.7 \, I_{REL}$$

$$S = I_{REL}$$

$$I_{PEAK} = \frac{P \, e^{-\alpha R} \, I_{REL}}{\pi a_f^2} \quad .$$

This model automatically gives the correct peak intensity and conserves total power. It also provides an excellent representation of the data in terms of the area within a given constant intensity contour and the eccentricity of the constant intensity contours.

These models, of course, are subject to the same limitations as the data from which they were derived. For example, they do not apply (unless suitably modified) in the presence of jitter or turbulence or when slewing is not in the same plane as the wind. Actually, the most significant result of this task is that both distortion and deflection are probably too minor to have a significant impact on system effectiveness.

4.3   REVIEW OF TASK III. BEAM QUALITY

The objective of this task was to develop an approach to modeling the effect of phase and amplitude aberrations in the aperture plane on the far-field beam profile. In more general terms, it was desired to obtain a rational approach to representing beam quality.

The recommended approach involves approximating the far-field intensity profile (neglecting blooming) as a Gaussian distribution of the form

$$I(R) = \cfrac{m_1 P_T e^{-\alpha_e R} \exp\left\{-\cfrac{r^2}{2R^2 \left(\cfrac{m_2^2 \sigma_{DL}^2}{I_{REL}} + \sigma_J^2 + \sigma_T^2\right)}\right\}}{2\pi R^2 \left(\cfrac{m_2^2 \sigma_{DL}^2}{m_1 I_{REL}} + \sigma_J^2 + \sigma_T^2\right)} \ .$$

The parameters m_1 and m_2 are the proposed beam quality
parameters and are determined so that the integrated power
distribution corresponding to the above expression matches
the actual distribution at two specified points, e.g.,
$r = w_f$ and $r = 2w_f$, where w_f is the beam waist.

This two parameter representation of beam quality
is a significant advance over the usual "m x diffraction
limited" concept. It can account both for power loss due
to wide angle scattering and for beam spreading. It should
be fully adequate to represent all situations in which the
far-field beam profile is dominated by a central lobe.
Furthermore, the general approach is sufficiently flexible
that it can include effects associated with beam truncation
and obscuration (see following section) as well as with
other amplitude perturbations and with phase aberrations.
For example, the simplified optical train model (OPTRAIN)
described in Section 2 provides a method of estimating m_1
and m_2 for a wide range of system parameters.

4.4   REVIEW OF TASK IV. BEAM TRUNCATION AND OBSCURATION

The effect of truncation and obscuration were inves-
tigated both analytically and within the empirical frame-
work of the beam quality model developed in Task III,

i.e., the results were presented in terms of the parameters m_1 and m_2. Detailed results of the analysis are presented in Reference 2. Since the degree of truncation and obscuration is determined by the optical train, the model itself has been incorporated into the optical train model (Section 2).

Section 5

CONCLUSIONS

In any high technology program, like the DOD laser program, it is important that technologists and analysts work together to resolve the issues and support the efforts of the other group. During the early phases of a new program the technologists severly bound the problem under study to facilitate modeling of complicated processes. On the other hand, the analysts use extremely simplistic models for the elements of the system under study because they must address every aspect of the problem albeit in a naive manner. As time passes these two groups move closer together with the theoreticians studying ever increasing segments of the problem and the systems analysts improving their models and studying the issues in greater depth.

The atmospheric propagation coding studied under this contract is really second generation modeling. Improving the speed and accuracy of a program, adding multi-line propagation, and studying beam shape are exemplary of the movement of HEL system analysts toward increasingly complex modeling. One of the other areas investigated -- the optical train analysis -- is less well developed. The detailed tools for modeling the beam propagation through the optical train have been operational only recently. Hence, the simplified codings developed under this contract are first generation models. The authors hope that both of these modeling tasks will contribute to the continuing covergence of laser technology and systems analysis.

APPENDIX A

Molecular Absorption of DF Laser Radiation

A.1   INTRODUCTION

This appendix was written by Dr. T. Tuer of the
Ann Arbor SAI office. This work was undertaken to provide
better values for the molecular absorption coefficients
used in the thermal blooming code. These coefficients
are required as a function of both altitude and of
atmospheric water vapor content for several "typical" DF
laser line groups. Here, "typical" means a characteristic
laser propagation-altitude function (this will be clarified
in Section A.3). For convenience in the thermal blooming code,
the coefficients are given as a simple analytical function
of altitude and water content, with different sets of
coefficients (i.e., one for each typical group).

A.2   APPROACH

Due to time constraints, it was decided to use
McClatchey's DF absorption coefficients (Reference A.1)
rather than re-calculating them with our own line-by-line
codes. The ten BDL laser lines that McClatchey considered
were selected for this study (see Table A-1). However,
since McClatchey did not include the water continuum
absorption in his calculations, it was necessary to add
this component. A simple computer program DAFT (DF
Altitude Fitting Code), was written to: (1) evaluate
this continuum component for the frequencies, altitudes
and model atmospheres desired, (2) add this to McClatchey's

A-1

results, and (3) plot the total absorption coefficient as a function of altitude.

Table A-1. List of DF-BDL Lines

DF Laser Line	Frequency (cm^{-1})	Relative Power	Considered by McClatchey and Here
$P_3(8)$	2546.37	10.7	yes
$P_3(7)$	2570.51	10.2	yes
$P_2(10)$	2580.16	6.2	yes
$P_3(6)$	2594.23	7.7	yes
$P_2(9)$	2605.87	9.7	yes
$P_3(5)$	2617.41	1.8	yes
$P_2(8)$	2631.09	12.9	yes
$P_2(7)$	2655.97	10.0	yes
$P_1(10)$	2665.20	3.9	yes
$P_2(6)$	2680.28	6.2	yes
$P_1(9)$	2691.41	9.1	no
$P_1(8)$	2717.54	6.6	no
$P_1(7)$	2743.03	3.5	no
$P_1(6)$	2767 91	2.0	no

The water continuum absorption coefficient is given by (Reference A.2).

$$n = c_S^0, _wP^*_w + c_N^0, _wP^*$$

where p_w is the partial pressure of water vapor, P is the total pressure and the * indicates the density-equivalent-

A-2

pressures[1]. This reference also gives measured values of c_{s,w_0}^0 as a function of frequency at 294^0 K[2], and recommends value of $c_{N,w}^0 = 0.12$ $c_{s,w}$. The absorption coefficient n differs from the usual coefficient k by:

$$k = nU/L$$

where U is the absorber thickness and L is the path length. Values for p*, P* and U were calculated as a function of altitude using data given by the Handbook of Geophysics and Space Environment (Reference A.3).

The attenuation of most of the DF laser lines is dominated by atmospheric water absorption (i.e., H_2O or HDO line absorption, or H_2O continuum absorption). In order to account for different atmospheric water content, the calculated absorption coefficient was normalized by:

$$k^* = k/\rho^*$$

Here ρ^* is a normalized water density-altitude profile which varies between a value of ρ_0^* at sea level, to unity as $h \to \infty$. The quantity ρ_0^* is the sea level density of the model atmosphere under consideration, normalized to that of the midlatitude summer model atmosphere. The form of ρ^* was arbitrarily taken to be:

$$\rho^* = 1 + (\rho_0^* - 1)10^{R/2}$$

_____

1. Since the pressures are generally less than one atmosphere, we used the usual pressure in place of the density-equivalent-pressure.

2. Since the temperature dependency of this quantity is uncertain, its value at $294^0 K$ was used throughout.

A-3

where R is the normalized water density profile based on
the data in Reference A.3 (see Figure A-1). An example of
the effect of this scaling is shown in Figure A-2, where
the absorption coefficient profiles for the five different
model atmospheres are seen to collapse nicely into a narrow
band.

Atmospheric
Model ρ_0

Tropical   19
Midlatitude Summer   14
Midlatitude Winter   3.5
Subarctic Summer   9.1
Subarctic Winter   1.2

$R = c_1 h + c_2 h^2$

$c_1 = 0.05075$

$c_2 = 0.00015$

$R = \log \rho$

Note: Water vapor density
(gm/m^3) can be con-
verted to precipitable
centimeters (pr. cm/km)
by dividing by 10.

Atmospheric Water Vapor Concentration ρ (gm/m^3)

Altitude (km)
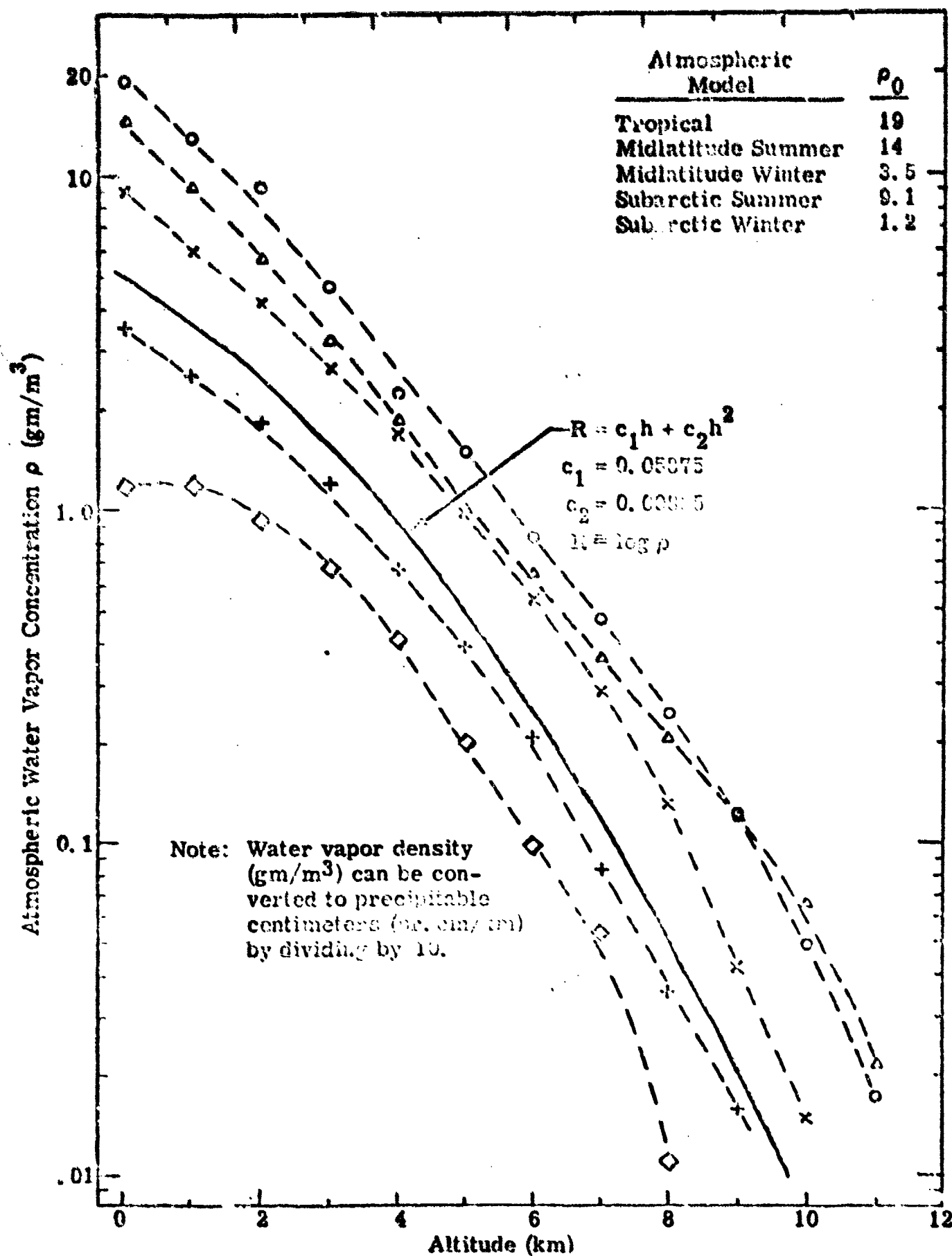
Figure A-1. Water Concentration Profiles for Five Model Atmospheres
             and Analytic Fit.

A-5
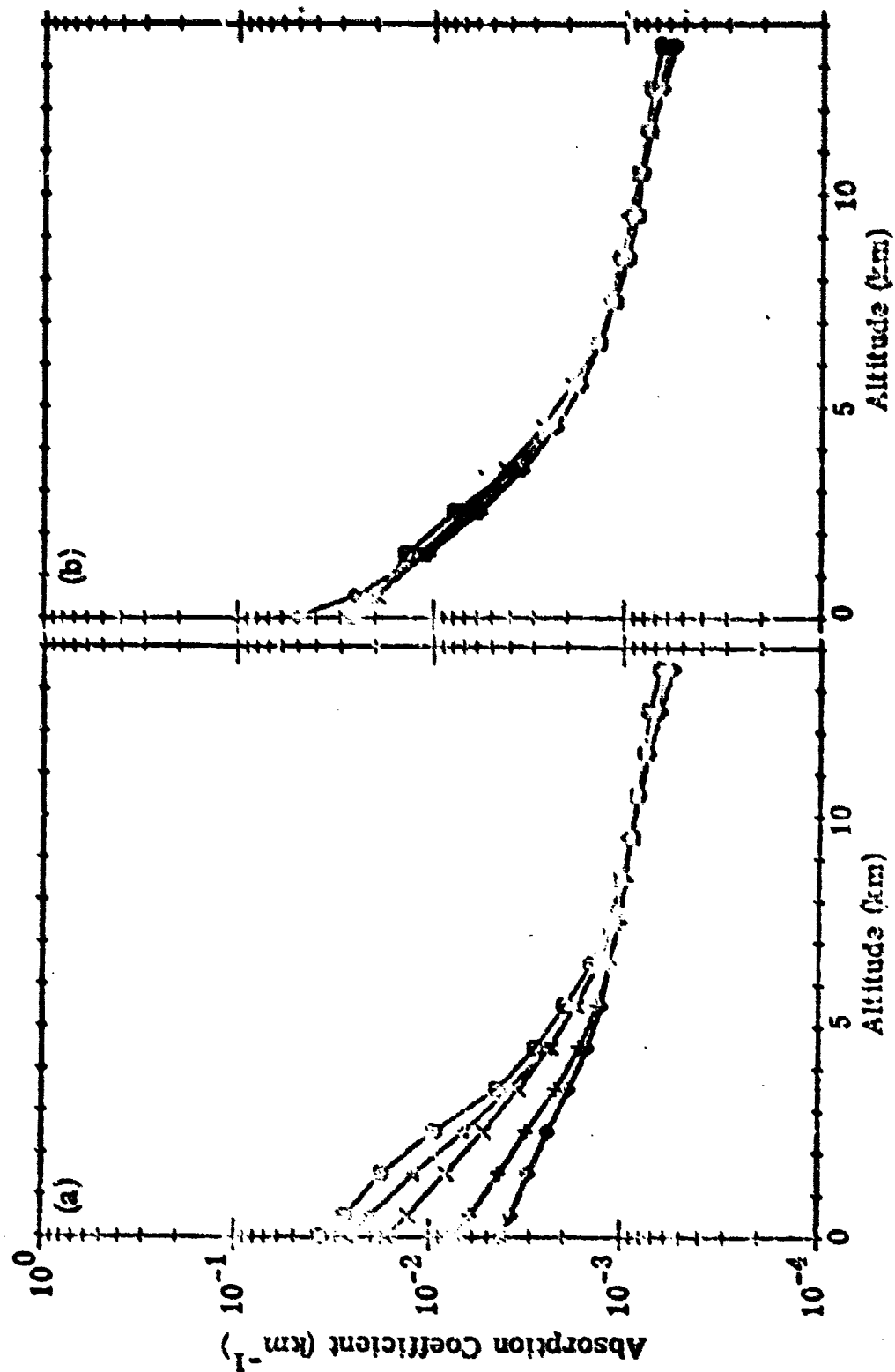
Figure A-2. Demonstration of the Effect of Scaling to Account for Various Atmospheric Water Concentrations - $P_2(8)$ DF Laser.
(a) No Scaling
(b) With Scaling

A.3   DETERMINING TYPICAL GROUPS

Normalized profiles for all the water dominated
laser lines were plotted on a common scale. Of course
the lines which are dominated by other species (e.g.,
N_2O line absorption), were not normalized in this fashion
but simply plotted. These plots tend to collect in three
general groups. Those laser lines which are dominated by
water at low altitudes, but happen to fall on underlying
absorption lines (Type A), have a knee in their profile
(see Figure A-3). Those that do not have underlying
lines (Type B), do not have a pronounced knee but continue
to decrease with altitude, at least for the altitude range
considered here (see Figure A-4). Lines which are not
dominated by water (Type C), have no knee but fall off
less rapidly with altitude (see Figure A-5).

The mechanism for each type can be elucidated by
examining the details of the absorbing lines and continuum.
Figure A-6 shows components of the absorption coefficient
of a Type A laser line at sea level. Notice the under-
lying CH_4 absorption line (M2), which will become important
at higher altitude as the absorption by water diminishes.
Figure A-7 shows a Type B laser line where there is no
important underlying absorption lines. Finally, a Type C
laser line is shown in Figure A-8, which is dominated by
N_2O absorption even at sea level, and is affected little
by water.

A.4   RESULTS

A least squares fit was applied to each group of
laser lines (i.e., Types A, B and C). The analytic form
used was:

$$\ln k^* = A_0 + A_1 h + A_2 h^2$$
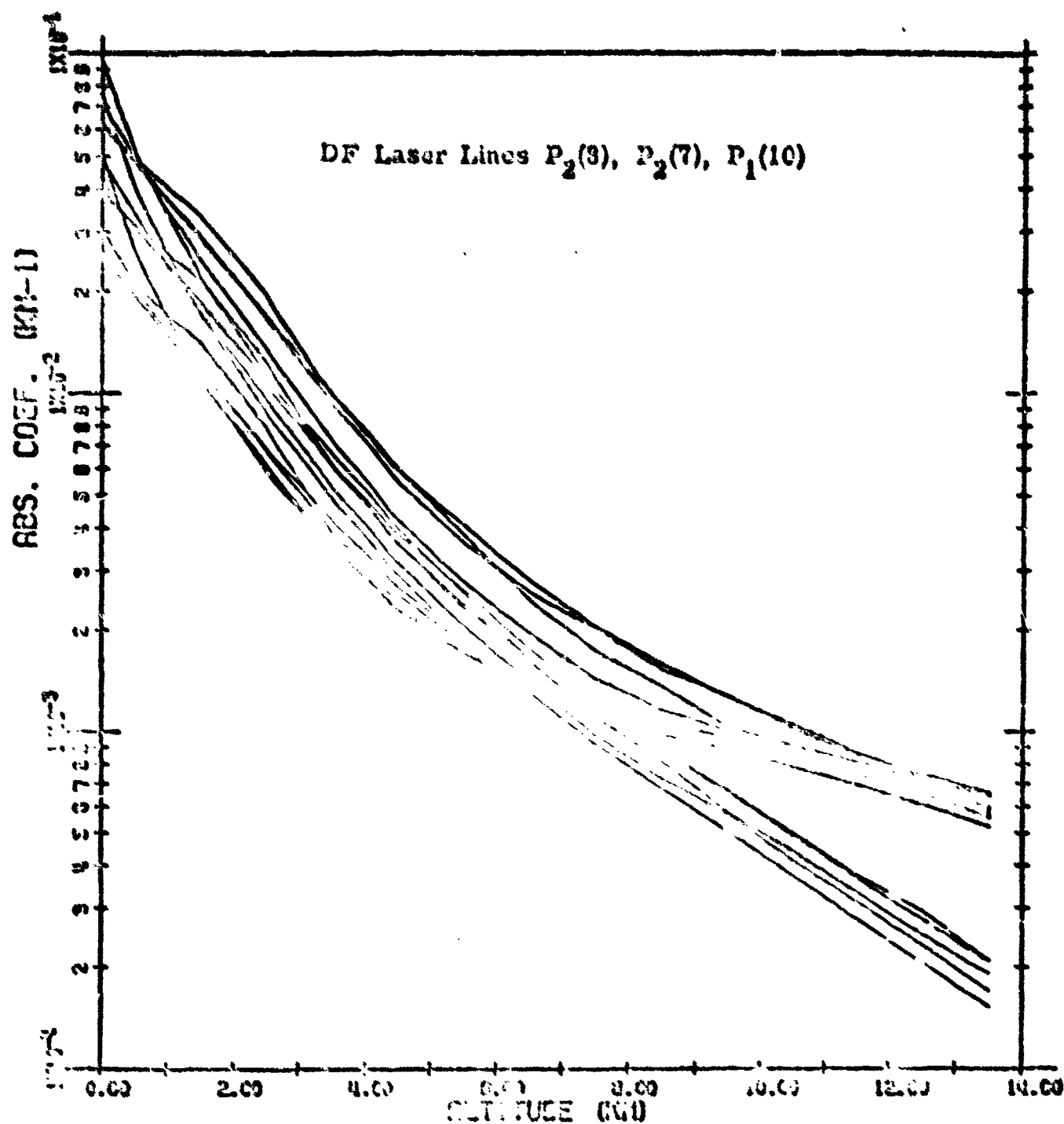
Figure A-3. Laser Propagation-Altitude Function Type A: Dominated by Water at Low Altitudes but with Underlying Absorption Lines which become Important at High Altitudes.
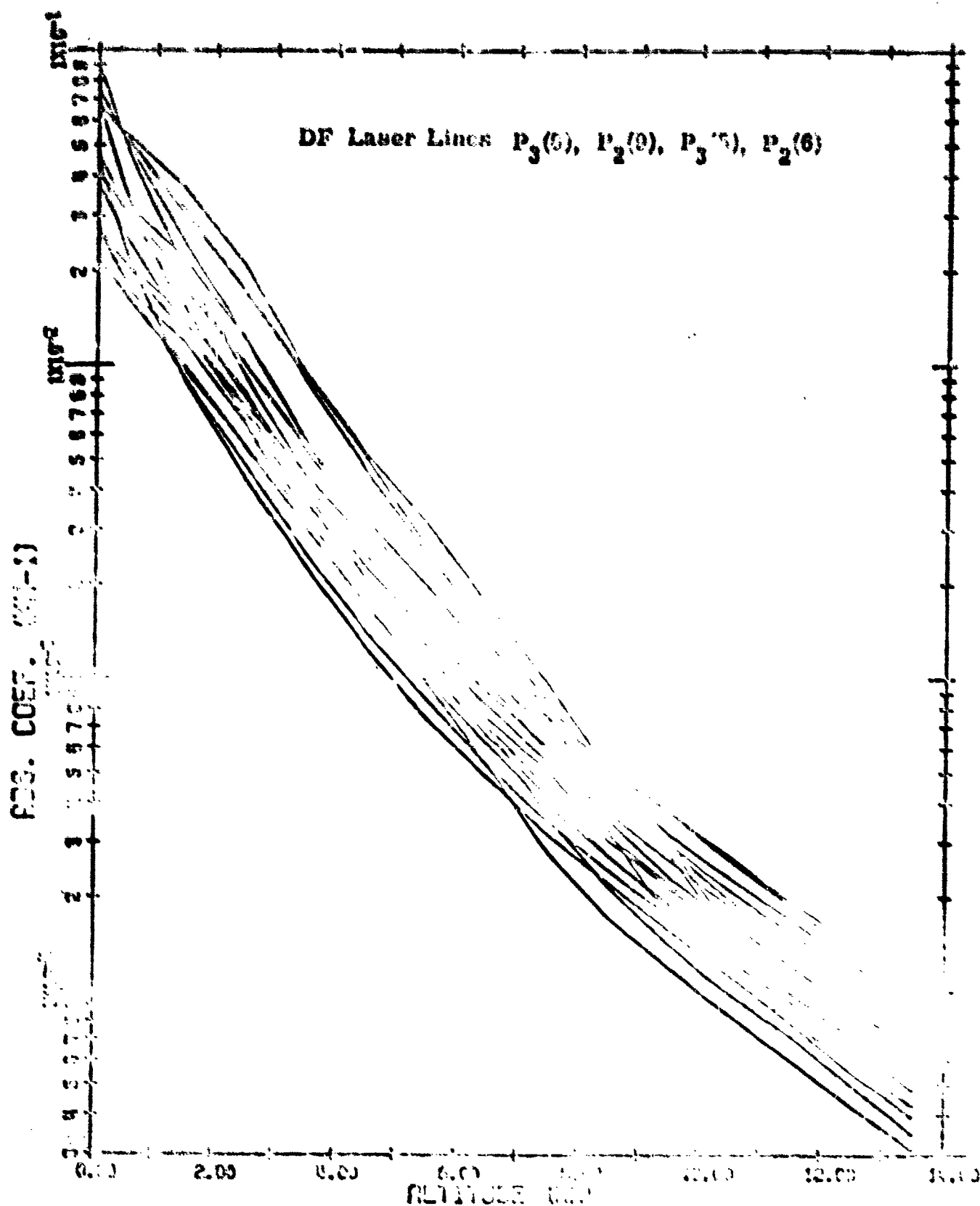
Figure A-4. Laser Propagation-Altitude Function Type B: Dominated by Water at Low Altitudes but with Underlying Absorption Lines which become Important at High Altitudes.

A-9
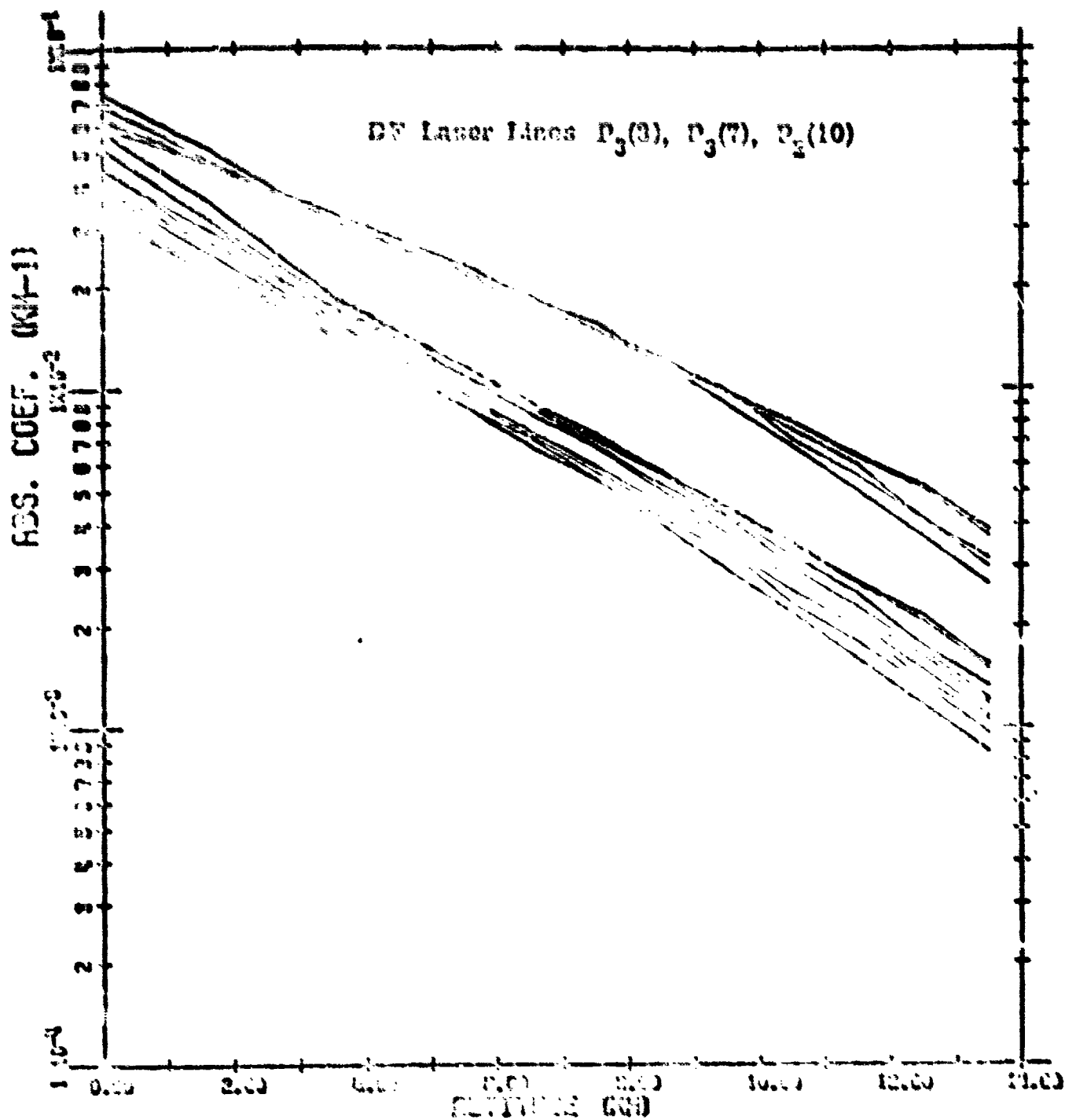
Figure A-5. Laser Pro... ...on-Altitude Function Type C: Dominated by Water at Low Altitudes but with Underlying Absorption Lines which become Important at High Altitudes.

A-10
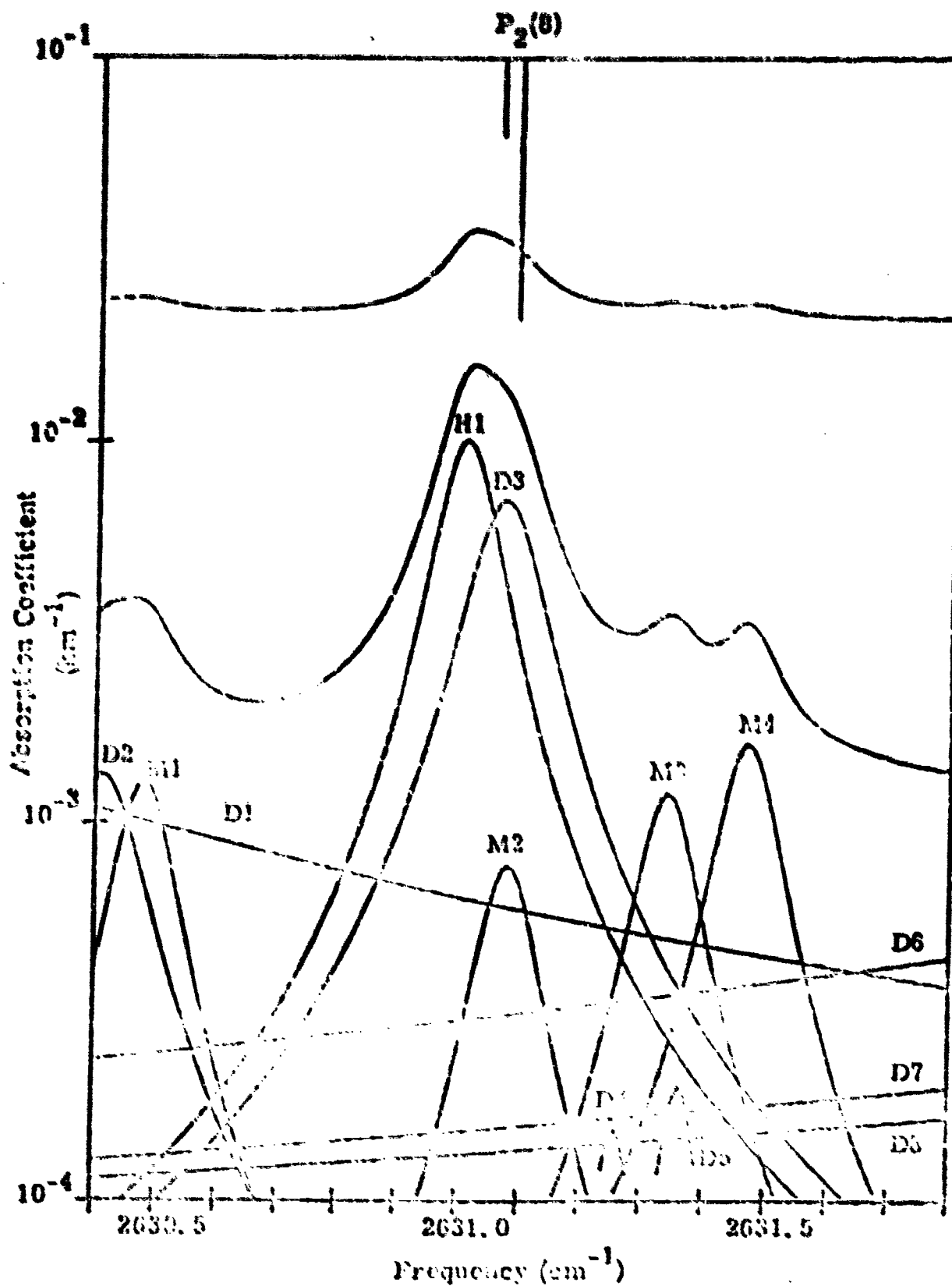
Figure A-6.   Contributors to the Molecular Absorption of the $P_2(8)$ DF Line (Midlatitude Summer, Sea Level).

Example of Type A Absorption, Extracted from Ref. A.4.
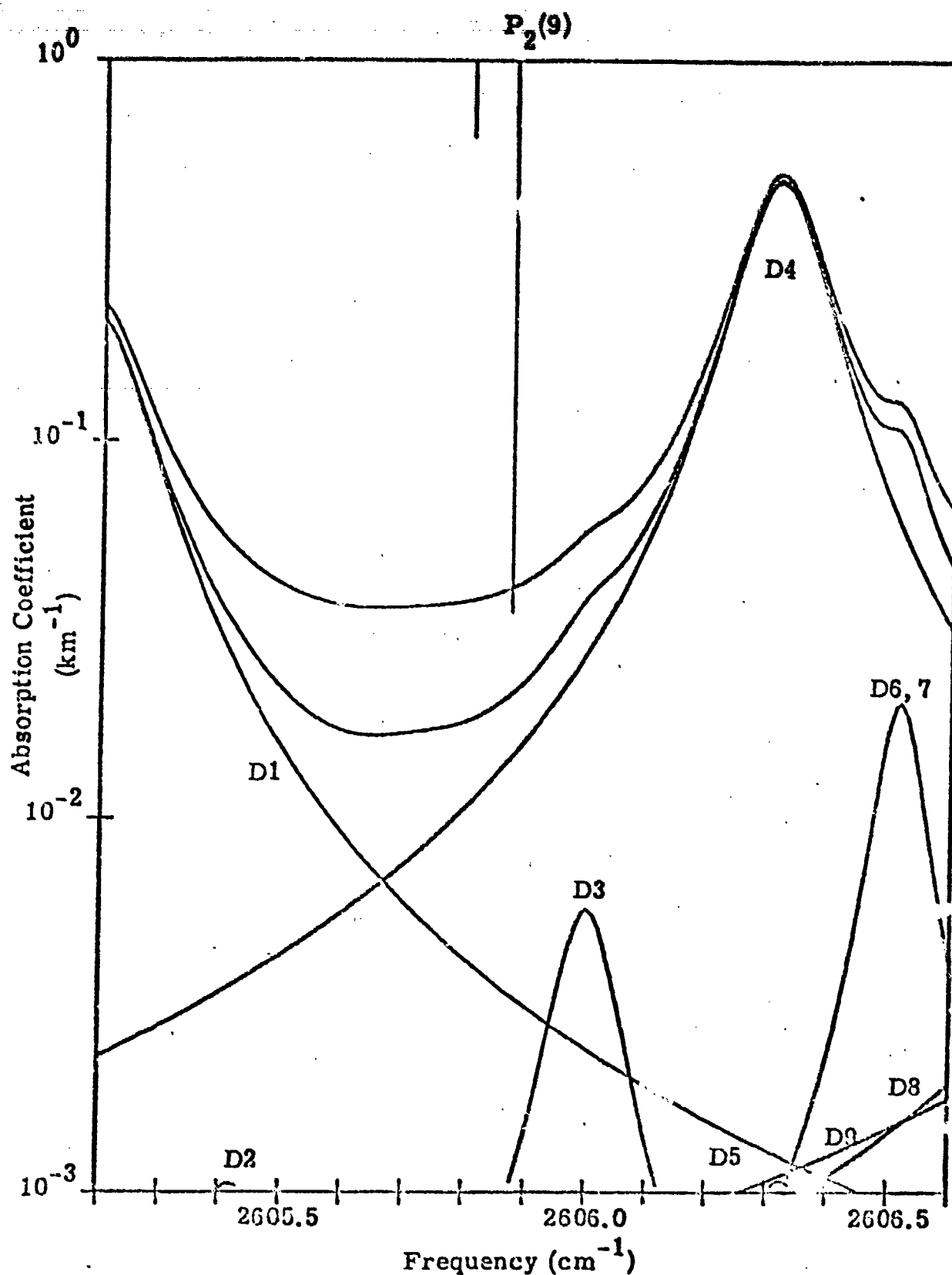
Figure A-7. Contributors to the Molecular Absorption of the $P_2(9)$ DF Line (Midlatitude Summer, Sea Level).

Example of Type B Absorption, Extracted from Ref. A.4
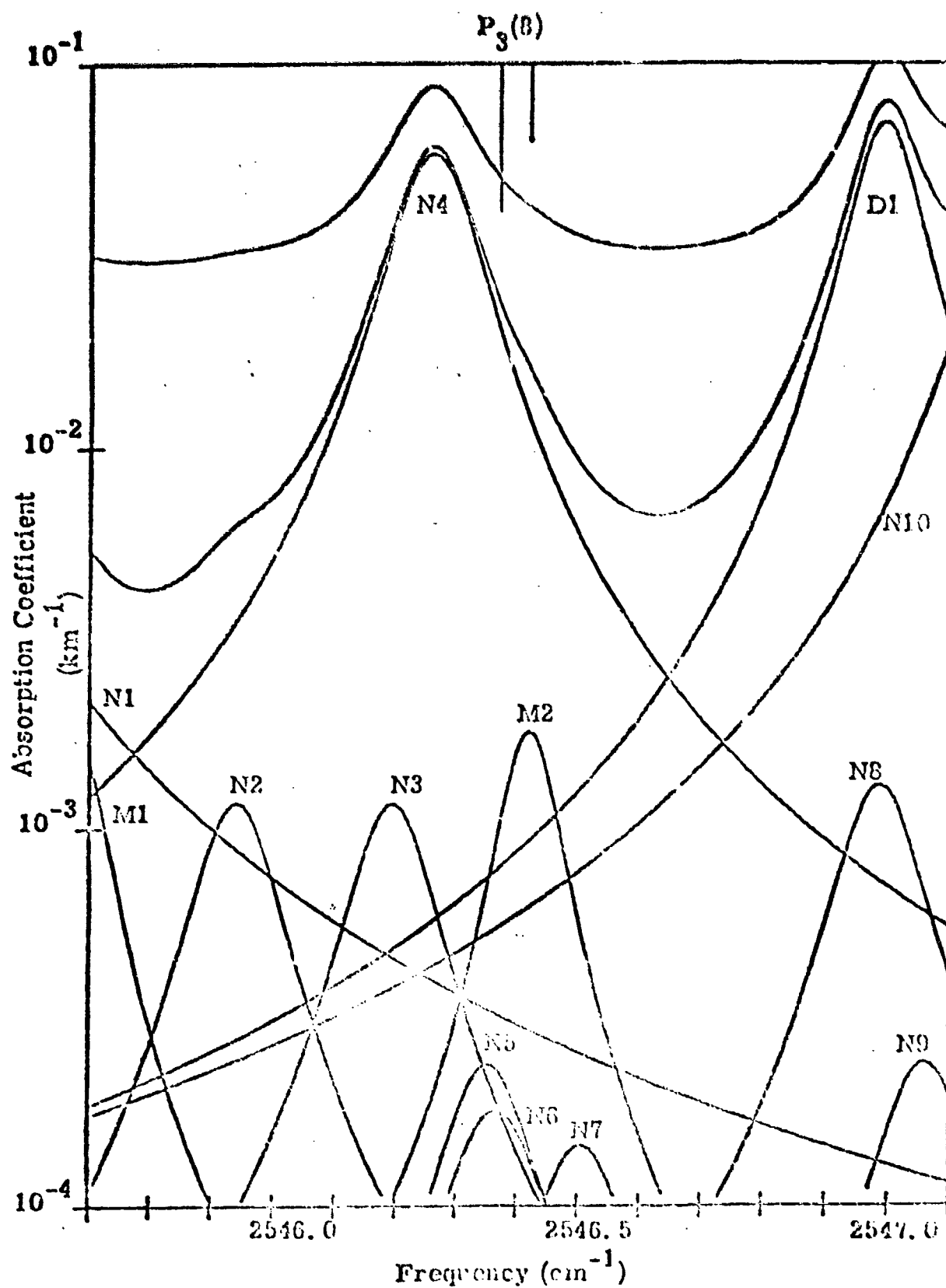
Figure A-8. Contributors to the Molecular Absorption of the $P_3(8)$ DF Line (Midlatitude Summer, Sea Level).

Example of Type C Absorption, Extracted from Ref. A.4

where k^* is the normalized absorption coefficient (km^{-1}) and h is the altitude (km). The results of this fit for each group are shown in Figures A-9 through A-11, and the determined coefficients (i.e., A_0, A_1, A_2) given in Table A-2.

Table A-2. Coefficients of Least Squares Fit

Type	DF Laser Lines	A_0	A_1	A_2
A	$P_2(8)$, $P_2(7)$, $P_1(10)$	-3.138	-0.6388	0.0225
B	$P_3(6)$, $P_2(9)$, $P_3(5)$, $P_2(6)$	-3.173	-0.6952	0.0155
C	$P_3(8)$, $P_3(7)$, $P_2(10)$	-3.039	-0.2199	-0.00196

For Type C laser lines this normalized coefficient k^* is identical to the un-normalized coefficient k (since water absorption is insignificant):

$$k = k^* \qquad \text{(for Type C)}$$

Type A and B lines must be un-normalized by:

$$k = \rho^* k^* \qquad \text{(for Types A \& B)}$$

where $\rho^* \equiv 1 + (\rho_0^* - 1)\, 10^{R/2}$ and:

$$R = C_1 h + C_2 h^2$$

with $C_1 = 0.05875$ and $C_2 = 0.00835$.
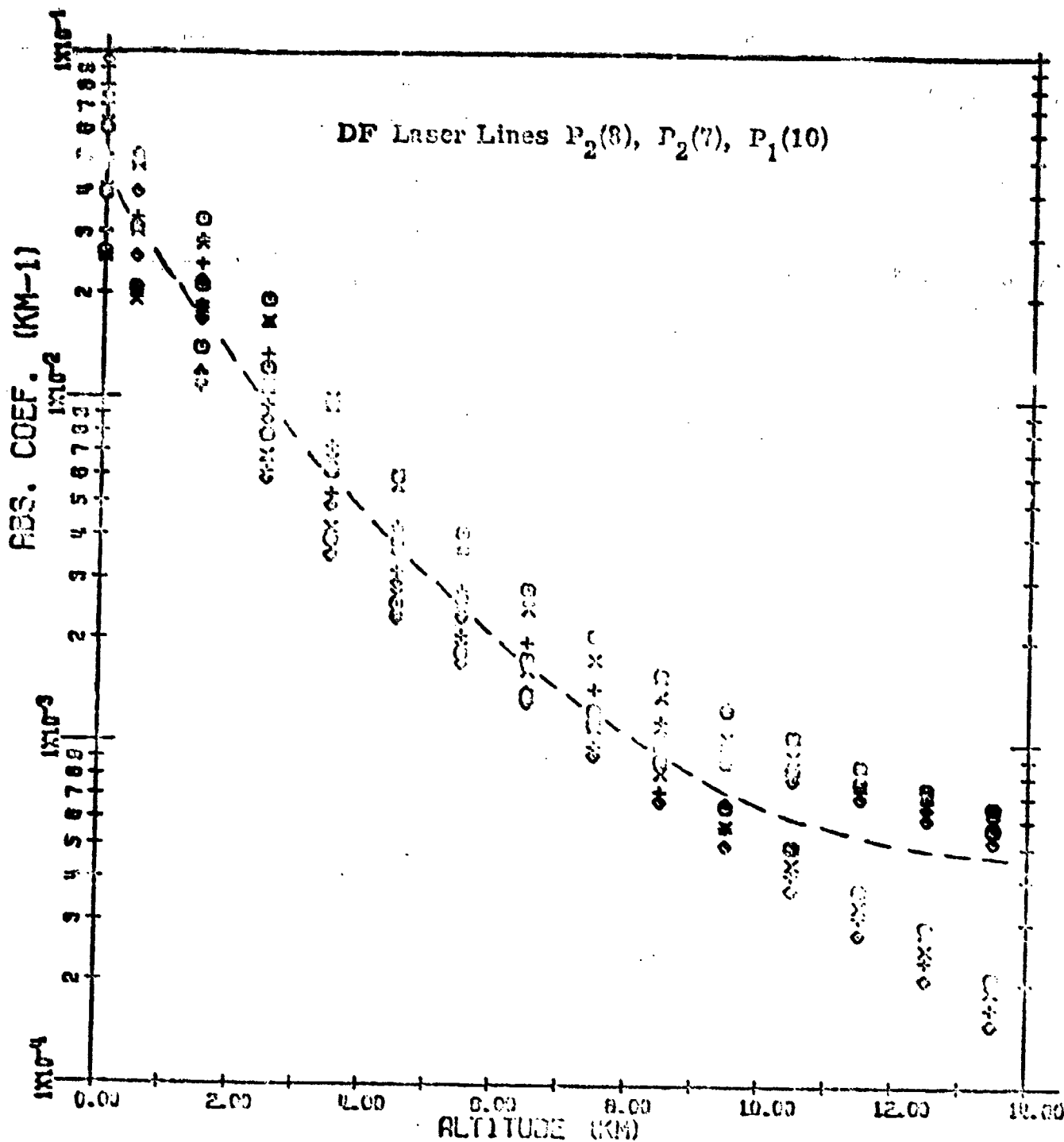
Figure A-9. Least Squares Fit to Type A Laser Lines

A-15
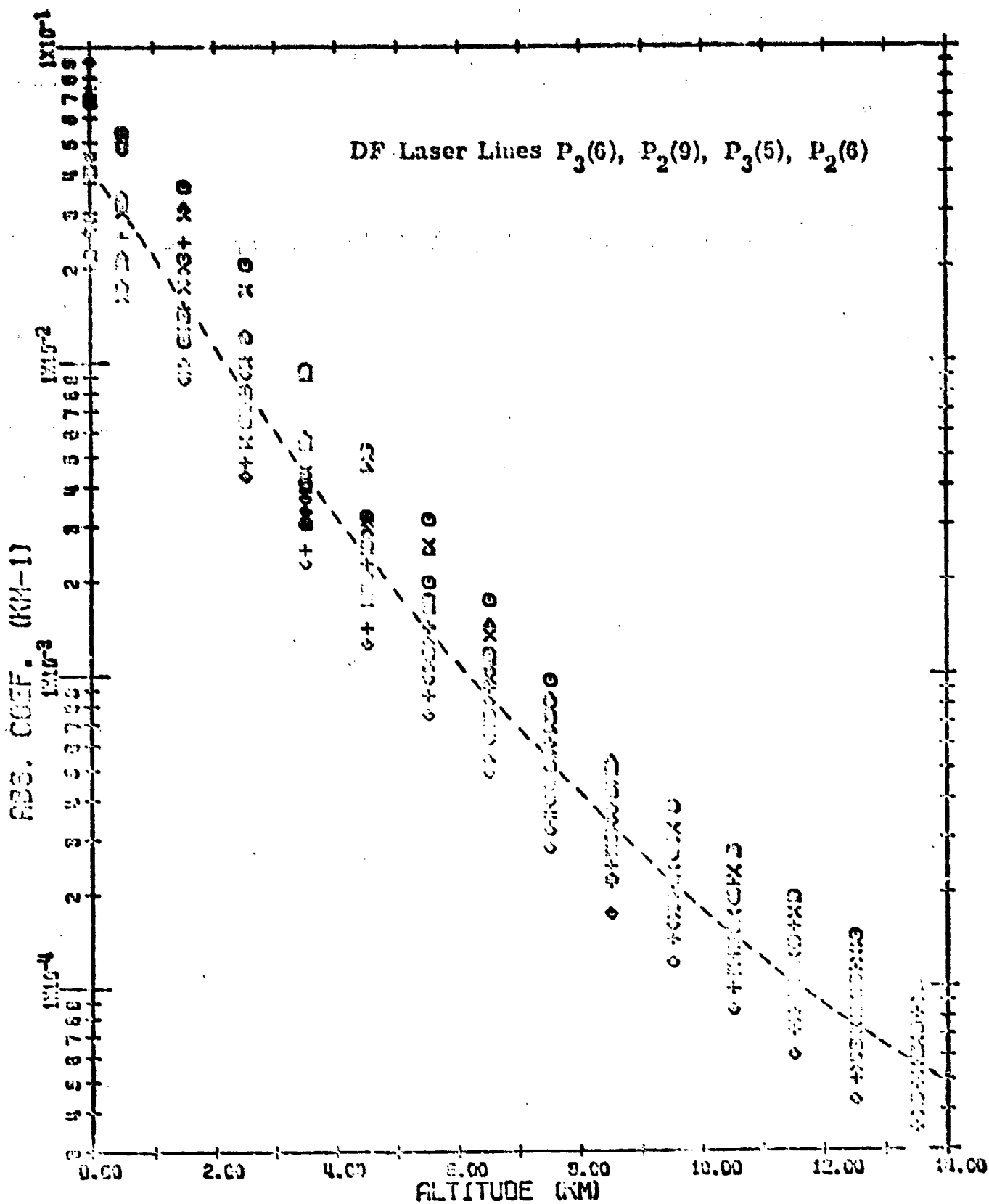
Figure A-10. Least Squares Fit to Type B Laser Lines

DF Laser Lines $P_3(8)$, $P_3(7)$, $P_2(10)$

Figure A-11. Least Squares Fit to Type C Laser Lines

A-17

APPENDIX B

APPENDIX B

```
          PROGRAM SAICOM(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)                    SIC    2
      C                                                                            SIC    3
      C   SAICOM IS THE EXECUTIVE ROUTINE WHICH READS THE INPUTS AND DEFINES       SIC    4
      C   THE CONDITIONS AT EXIT OF THE TELESCOPE.                                 SIC    5
      C                                                                            SIC    6
          LOGICAL ERR                                                              SIC    7
          EQUIVALENCE (RO,PO)                                                      SIC    8
          EQUIVALENCE (HOM,ROM)                                                    SIC    9
          INTEGER BEAM,BEAM,DEBUG,OUT,PROP,SPOT,TITLE(7),WTMR                       SIC   10
          REAL IRD,L,LAMDA,M,M1,M2                                                 SIC   11
      C                                                                            SIC   12
          COMMON /ERROR/ ERR                                                       SIC   13
          COMMON /ATMIN/ M,OI,PROP,SIGLF,SIGHF,WTMR,M1,M2                          SIC   14
          COMMON /ATMS/ BEAM,FL,GL,MTM,IRD,L,LAMDA,NSTEP,PHI                       SIC   15
          COMMON /IN/ COEF2,MOM,RI                                                 SIC   16
          COMMON /INS/ DEBUG,ITYPE,OUT,PT,RO                                       SIC   17
          COMMON /INT/ PD                                                          SIC   18
          COMMON /ALFA/ LAM,RH                                                     SIC   19
          COMMON /OPTIN/ DR,PIN,HL,EPS,XNL,DT,XRI,TMI,DIOVI,DLI,DELTAR,RMEF,        SIC   20
         1XLC,DC,N,REFL,SFAR,ITYPEM,XLMIR,XMAG,DTR,ITYPEH,XLEA,BETA,ASAB,ITY        TCP   21
         2PEA,THTR,THPS,THAC,IMSV,DIT,DELT,ITYPAW                                   SIC   23
          COMMON /OPTOUT/ DBT,P,XM1,XM2,TH                                         SIC   24
          COMMON /X/ CHI,OMEGA,VP,VPSC,VFR                                         SIC   25
      C                                                                            SIC   26
          DIMENSION IBEAM(2), IDEBUG(2), ISI(3), IS(3), IJTYPE(4), IOUT(2), IPROP(3  SIC   27
         1)                                                                        SIC   28
      C                                                                            SIC   29
          NAMELIST /INPUT/ BEAM,CHI,DEBUG,FL,GL,MTM,MOM,IBD,LAMDA,M,NSTEP,OM        SIC   30
         1EGA,OUT,PHI,PROP,RH,RI,RO,SIGHF,SIGLF,VP,VKS,WTMR                        SIC   31
          NAMELIST /CASE/ DB,EPS,DT,XRI,TMI,DIOVI,DLI,DELTAR,RMEF,XLC,DC,N,R        SIC   32
         1EFL,SFAR,ITYPEM,XLMIR,XMAG,TAPE,ITYPEB,XLEA,BETA,ASAB,ITYPEA,THTR,        TCP    2
         27HAS,IMAA,IMSV,DELT,ITYPAW                                               SIC   34
      C                                                                            SIC   35
          DATA IBEAM/10HCOLLIMATED,10HFOCUSED    /                                 SIC   36
          DATA IDEBUG/10HOUT DEBUG ,10H DEBUG   /                                  SIC   37
          DATA IIW/10HMILD    ,10HNORMAL    ,10HSEVERE     /                       SIC   38
          DATA IOUT/5HSHORT,5H LONG/                                               SIC   39
          DATA IPROP/10HGAUSSIAN  ,10HPLANE WAVE,10HIAF GAUSS /                    TCP    2
      C                                                                            SIC   40
          READ (5,7) NRUNS                                                         SIC   41
          DO 6 IRUNS=1,NRUNS                                                       SIC   42
      C                                                                            SIC   43
      C   READ REQUIRED INPUTS                                                     SIC   44
          READ (5,8) TITLE                                                         SIC   45
          READ (5,9) ITYPE,PD,PT,OI,L                                             SIC   46
      C                                                                            SIC   47
      C   SET DEFAULT VALUES OF OPTIONAL PROPAGATION INPUTS                        SIC   48
          IF (OI.EQ.0.) OI=1.E7                                                    SIC   49
          BEAM=1                                                                   SIC   50
          CHI=.52                                                                  SIC   51
          DEBUG=1                                                                  SIC   52
          FL=L                                                                     SIC   53
          GL=0.                                                                    SIC   54
          MTM=10.                                                                  SIC   55
          MOM=50.                                                                  SIC   56
          IBD=1E12                                                                 SIC   57
          LAMDA=3.8E-6                                                             SIC   58
```

```
                M=1.5                                       SIC      59
                NSTEP=30                                    SIC      60
                OMEGA=0.                                    SIC      61
                OUT=1                                       SIC      62
                PHI=-1.E-6                                  SIC      63
                PROP=1                                      SIC      64
                RM=.5                                       SIC      65
                KI=.08                                      SIC      66
                RO=.35                                      SIC      67
                SIGMF=5.E-6                                 SIC      68
                SIGLF=5.E-6                                 SIC      69
                VXM=0.                                      SIC      70
                VP=15.                                      SIC      71
                WTMM=0                                      SIC      72
        C                                                   SIC      73
        C       READ (5,INPUT)                              SIC      74
                                                            SIC      75
                BEAM=BEAM+1                                 SIC      76
                IW=WTHR+2                                   SIC      77
                ERM=.FALSE.                                 SIC      78
        C       IF (VXM.NE.0.) VP=0.0                       SIC      79
                                                            SIC      80
        C       IF (PD.EQ.0.0) GO TO 1                      SIC      81
                                                            SIC      82
        C       SET DEFAULT VALUES FOR OPTICAL TRAIN        SIC      83
        C                                                   SIC      84
        C       TMI=SQRT(SIGMF*SIGMF*SIGLF*SIGLF)           SIC      85
                WL=AHS(LAMDA)                               SIC      86
                PIM=PC                                      SIC      87
                AML=M                                       SIC      88
                DIT=2.*RI                                   SIC      89
                DIM=2.*RO                                   SIC      90
                DM=.15                                      SIC      91
                EPS=.36                                     SIC      92
                DT=2.0                                      SIC      93
                XPI=1.E70                                   SIC      94
                DIOVI=0.5                                   SIC      95
                DLI=0.1                                     SIC      96
                DELTAM=0.1                                  SIC      97
                PREF=2.5                                    SIC      98
                XLC=50.                                     SIC      99
                DC=.166                                     SIC     100
                N=7                                         SIC     101
                REFL=.986                                   SIC     102
                SFAR=1./8.                                  SIC     103
                ITYPEM=1                                    SIC     104
                XLMIP=.15                                   SIC     105
                XMAG=4.375                                  SIC     106
                ITYPEH=1                                    SIC     107
                ITYPEA=1                                    SIC     108
                XLE4=.05                                    SIC     109
                AETA=.01                                    SIC     110
                ASAA=.05                                    SIC     111
                TMTP=5.E-6                                  SIC     112
                TMMS=5.E-6                                  SIC     113
                IHAA=5.E-6                                  SIC     114
                THCM=5.E-6                                  SIC     115
```

```
            DELT = 1.0
            ITYPAN = 1
      C
            READ (5,CASE)
      C
      C     WRITE INPUTS
            IF (PHI.NE.-1.E-6) HTM=9.0
            HOF=3.201+DOM
            HTF=3.781+HTM
            WRITE (6,10) TITLE
            IF (ITYPE.EQ.5) GO TO 2
            WRITE (6,11) IOUT(OUT),IOEBUG(DEBUG),...,?,FL,PT
            GO TO 3
          2 WRITE (6,12) IOUT(OUT),IDEBUG(DEBUG),OI,PD,FL,PT
          3 WRITE (6,13) FL,LAND,HDM,SIGMF,HDF,SIGLF,HTM,OMEGA,MTF,RO,PHI,R2
            WRITE (6,14) CHI,IPROP(PROP),VP,IHEAM(MEAN),VXS,M,ISW(SW),NSTEP,BM
      C
      C     OPTICAL TRAIN CALCULATIONS
      C
            IF (PD.EQ.0.) GO TO 4
            CALL OPTRAIN
            RC=ORF/2.
            PT=D
            M1=XM1
            M2=XM2
            SIGMF=TH
            SIGLF=0.
            IF (PROP.EQ.?) GO TO 5
            M1=XM1/.89
            IF (PROP.EQ.1) M2=1.622*XM2
            IF (PROP.EQ.3) M2=XM2/1.29
            GO TO 5
      C
      C     SPECIFICATION OF BEAM QUALITY FOR PD = 0
      C     (TRUNCATED GAUSSIAN)
          4 M1=1.
            M2=1.4104
            IF (PROP.EQ.1) GO TO 5
      C     (INFINITE GAUSSIAN)
            M2=4
            IF (PROP.EQ.3) GO TO 5
      C     (PLANE WAVE)
            M1=0.89
            M2=1.29*M
          5 WRITE (6,15) M1,M2
            CALL ATM
      C
          6 CONTINUE
            STOP 61
      C
```

```
       C
       7          FORMAT (12)
       8          FORMAT (7A10)
       9          FORMAT (12.8X,6E10.0)
      10          FORMAT (1H1,30X,7A10/)
      11          FORMAT(///,10X,65.20H OUTPUT FORMAT, WITH,A10,//,10X,40HTARGET RAN
                  1GE (L) -----------------,1PE10.3,* METERS*,5X,34HDEVICE POWER
                  2 (PD) -----------------,1PE10.3,* WATTS*,/,10X,40HFOCAL DISTANCE (FL)
                  3-----------------, E10.3,* METERS*,5X,40HPOWER OUT OF THE TELESCO
      12          40E (PT) ---*, 1PE10.3,* WATTS*,//)
                  FORMAT (///,10X,65.20H OUTPUT FORMAT, WITH,A10,//,10X,40HDESIRED I
                  1NTENSITY (0I) -----------------,1PE9.2,* WATTS/*40*,3H**22X34HDEVICE
                  2 POWER (PD) -----------------,E10.3,* WATTS*,//,10X,40HFOCAL DISTANC
      13          3E (FL) -----------------,0PF4.0,* METERS*,6X, 34HPOWER OUT OF TH
                  4E TELESCOPE (PT) ---,1PE10.3,* WATTS*,//)
                  FORMAT (10X,60HGROUND LEVEL (GL) -----------------,0PF5.0,*
                  1 METERS*,6X,34H*AVELENGTH (LAMDA) -----------------,1PE9.2,* METERS
                  2*,/10X,40H DEVICE ALTITUDE (HGT) -----------------,0PF9.2,* METERS*,
                  3 35H*INPUT JITTER (HIGH FREQUENCY) ---, 1PE9.2,50X,1PE9.2,* FE
                  4ET*,21X*                  *1LOX FREQUENCY) ---*,1PE9.2/10X,40HTARGET ALTITU
      14          5DE (HT) -----------------,0PF5.2,* METERS*,6X,34HTRACKING RATE (CM
                  6EM) -----------------,0PF5.2,* RADIANS/SEC*,50X,1PE9.2,*  FEET*,6X,
                  60HOPTICS RADIUS (RO) -----------------,0PF6.2,* METERS*/10X,40HVERTICA
                  7L ANGLE (VMI) -----------------,0PF7.3,
                  8      *   RADIANS*,   6X,0HOBSCURATION RADIUS (RI) -----------------,0PF6.2,
      15          90 METERS*,//)
                  FORMAT (10X, *AZIMUTH ANGLE (CMI) -----------------,0PF7.3,
                  1* RADIANS*,6X,6EAM TYPE (PHOI) -----------------, A10,//,10X,
                  2*PLATFORM VELOCITY (VP) -----------------, 0PF7.0,*METERS/SEC*,5X,
                  3*TYPE OF PROPAGATION (BEAM) -----------------, A10,/,10X,*SPECIFIED CROSS
                  4 WIND (VXH) -----------------,0PF6.2,1H,, *BEAM QUALITY (M) -----------------*,
                  5 -----,0PF6.2,/,10X,*SEVERITY OF TURBULENCE (NT/R) -----------------*,
                  6A6,15X,*NUMBER OF REAR PATH INCREMENTS -----,
                  61?,/,10X, *RELATIVE HUMIDITY (XH) -----------------,0PF4.2//)
                  FORMAT (10X,*RESULTANT MEAN QUALITY*,5X,3H ) = *,F5.3,5X,042 = *,
                  1F5.3)
                  END
```

```
C            SUBROUTINE OPTRAIN                                          OPT      2
C                                                                       OPT      3
C     OPTRAIN CALCULATES THE POWER LOSSES, BEAM QUALITY DEGRADATIONS, AND OPT    4
C     JITTER INDUCED BY THE OPTICAL TRAIN EXTERNAL TO THE DEVICE.       OPT      5
C                                                                       OPT      6
      REAL IOPS,LC,L41R,LBE,LEA,LT,M1,M2                                OPT      7
      REAL LM,MAG                                                       OPT      8
C                                                                       OPT      9
      COMMON /OPTIN/ DSK,PI,AL,EPSI,DUAL,DT,RI,THI,DIOV1,DL1,DELTAR,RREF OPT    10
     1,LC,DC,N,REFL,SFA9,ITVPEM,LM1R,MAG,DTR,ITVPE8,LEA,BETA,ASA8,ITVPE4 OPT    11
     2,THM,THHS,THAS,T,M1,M2,TM                                         TCP      5
      COMMON /OPTOUT/ D2,P,M1,M2,TM                                     OPT     13
      COMMON /OPTOUT/ D2,P,M1,M2,TM                                     OPT     14
C                                                                       TCP      6
      DIMENSION MM(2),MA(2),MB(2),MAW(2)                                OPT     15
C                                                                       OPT     16
      DATA MM/AMON-AA1  ,SMOFF-AX1S/                                    OPT     17
      DATA MA/AMCOOLED  ,BMU,COOLED/                                    OPT     18
      DATA MB/6R=1.0774,6RDUAL/                                        OPT     19
      DATA MA/7=FOCUSED, 9=UNFOCUSED/                                   TCP      7
      DATA MLR/RM      /                                                OPT     20
C                                                                       OPT     21
      DBI=DTR                                                           OPT     22
      7V=0.0                                                            OPT     23
      OUE=1.0                                                           OPT     24
      RIG=1.E70                                                         OPT     25
      WRITE (6,18)                                                      OPT     26
      WRITE (6,18) DSI,PI,AL,EPSI,DUAL,DT,RI,THI,DIOV1                  OPT     27
      WRITE (6,79) DLI,MAG(ITVPE4),DELTAR,RREF,LC,DC,N,REFL,SFA9,MM(ITVPE TCP     8
     AM)                                                                TCP      9
      WRITE(6,21) LMIP,MAG,DTR,MM(ITVPE8),MA(ITVPEA),LEA,BETA,DELT,ASA8  TCP     10
      WRITE (6,22) THM,THHS,THSV,THA,TM=A                               OPT     30
      IF OUT BEAM CALCULATIONS                                         OPT     31
      1+VS=4.2PI*DIOVI/(10.833*DBI*DBI)                                 OPT     32
      SI=0.                                                             OPT     33
      IF (DUAL.GT.1.01 SI=SQRT(-ALOG((1.-EXP(-4.9348/DUAL/DUAL))/.992808 OPT    34
     12I)                                                               OPT     35
C                                                                       OPT     36
C     AERODYNAMIC M1=.004                                               OPT     37
      SA=1.45228E-5*DAT+DELTAR*RREF/M                                   OPT     38
      IF(ITV=4  .EG. 1) SA=0.0                                          TCP     11
C                                                                       OPT     39
C     BEAM CLIPPER                                                      OPT     40
      FU=CHS*DM1/(4.*4L*LC)                                             OPT     41
      A=.11C/SQRT(FU)                                                   TCP     12
      CAD=0M1/(1.-A)                                                    OPT     43
      DBIN=DM1*(EPSI-A)                                                 OPT     44
      IF (DBIN.LT.0.) DBIN=0.                                           OPT     45
      TC=1.0                                                            OPT     46
      DHI=DBO                                                           OPT     47
      IF (DM1.LE.OC) GO TO 1                                            OPT     48
      TC=(OC/DM1)**2                                                    OPT     49
      D=1=CC                                                            OPT     50
      CONTINUE                                                          OPT     51
C                                                                       OPT     52
    1 RELAY MIRROR                                                      OPT     53
C     S=CHS                                                             OPT     54
C     TM=REFL**N                                                        OPT     55
```

```
SUBROUTINE OPTRAIN    73/74    OPT=0    TRACE              FTN 4.8+P357        04/06/73  12.10.03.  PAGE   2

        SFAP=6.283190.545E-6*IFAB/WL                                      OPT      56
        GO TO (2,3), ITYPEH                                               OPT      57
  C     COOLED MIRRORS                                                    OPT      58
  2     CO=5.E-14*6.283190/WL                                             OPT      59
        SHI*CON=(1.0-REFL)*IRMS                                           OPT      60
        FINV=0.0                                                          OPT      61
        GO TO 4                                                           OPT      62
  C     UNCOOLED MIRRORS                                                  OPT      63
  C                                                                       OPT      64
  3     RHO=2.205E6                                                       OPT      65
        CP=0.02                                                           OPT      66
        COND=0.013E2                                                      OPT      67
        ALFA=3.E-8                                                        OPT      68
        TMK=.10                                                           OPT      69
        F=1.E70                                                           OPT      70
        IF (REFL.LT.1.0) F=.707*THK X1*DS*SQRT(CP*RHO*COND/DT)/(2.2091*   OPT      71
       1ALFA*(1.-REFL))                                                   OPT      72
        SHI*=3.1415*(1.0-REFL)*ALFA*DT*(RMS/(WL*CP*RHO)                   OPT      73
        FINV=1.0/F                                                        OPT      74
  C                                                                       OPT      75
        SHSG=SHI*(SFAP**2)*((N-1)*SHI*SHI/MAG/MAG)**2                     TCB      76
        SHS=SHI(SMSG)                                                     OPT      77
        LM=0.                                                             OPT      78
        IF (SMSQ.GT.0.) LM=DLI*N*N*SHI*SHI/SMSQ                           OPT      79
        A=1.0                                                             OPT      80
        B=LMIR                                                            OPT      81
        C=FINV                                                            OPT      82
        D=LMIR*FINV*1.0                                                   OPT      83
        DO 5 K=2,N                                                        OPT      84
        A=A*LMIR*C                                                        OPT      85
        B=B*LMIR*D                                                        OPT      86
        C=C*FINV*A                                                        OPT      87
        D=D*FINV*B                                                        OPT      88
  5     CONTINUE                                                          OPT      89
        R2=(A+B/A11)/(C+D/A11)                                            OPT      90
  C                                                                       OPT      91
  C     BEAM EXPANDER                                                     OPT      92
        R2=24G*F2                                                         OPT      93
        DO=DIV/MAG                                                        OPT      94
        D1=D1/MAG                                                         OPT      95
        C=DW1**2-D*IN**2                                                  OPT      96
        GO TO (6,10), ITYPEB                                             OPT      97
  C     ON-AXIS                                                           OPT      98
  6     IF (D*I.LE.D0) GO TO 8                                            OPT      99
        IF (DW1H.LE.D1) GO TO 7                                           OPT     100
        TRE=(D0**2-D*IN**2)/C                                             OPT     101
        E=DAIN/HO                                                         OPT     102
        CA=24G*D0                                                         OPT     103
        GO TO 12                                                          OPT     104
  7     TRE=(D0**2-D1**2)/C                                               OPT     105
        E=D1/D0                                                           OPT     106
        CA=44G*D0                                                         OPT     107
        GO TO 12                                                          OPT     108
  8     IF (DW1*.LE.D1) GO TO 9                                           OPT     109
        TRE=1.0                                                           OPT     110
        E=DAIN/DAI                                                        OPT     111
```

B-7

```
115          DB=MAG*DBI
             GO TO 12
        *    TBE=(DBI**2-DI**2)/C
             E=DI/DBI
             DB=MAG*DBI
120          GO TO 12
        C    OFF-AXIS
        C
       10    IF (DBI.LE.DO) GO TO 18
             THE=(DO/DBI)**2
             E=O-DO/DBI
125          DB=MAG*DO
             GO TO 12
       11    THE=1.0
             E=O-DO/DBI
130          DB=MAG*DBI
        C    COMPUTE QUALITY LOSS DUE TO CENTRAL OBSCURATION
        C
       12    SHE=0.0
             LHE=0.0
             IF (E.LE.0.) GO TO 13
135          A=.65411113601+.18640714840*E-.63216733220*E+2.34363043*E*E*E
             B=2.29734257-3.11550116*E+30.78787879*E*E-26.75996676*E*E*E
             SEE=S.3T(A*4-.43711257)
             LBE=(A*4-.19621804+53)/(SBE+SHE)
140     C    EXIT APERTURE
        C    SST=SQRT(FSAH)
       13    GO TO ((14+151, ITYPEA
        C
        C    SCL10 WINDOW
145    14    TEA=EXP(-HETA*LEA)*(1.0-ASAB)
             SEA=5.E-12*DT*BETA*LEA*IRMS*6.28319/WL
             THE=0.
             GO TO 14
             OPE=y WOOT
150    15    TEA=1.0-ASAB
             SEA=0.5
             THE=2.14E-7*(((LEA**3)*(DELT**6)/(WL*DB*DB);)**.2)
       16    CONTINUE
        C
155     C    COMPUTE TOTAL DISTORTION
             SD=-.3312*SI**2+SA**2+SH*2+SU**2+SE**2+SS1**2
             SS=SRT(SD)
             LI=1.0*214D*DLI*(((H-1)*SH1+SH1*MAG/MAG)**2)+LBE*SBE*SBE-DLI*SEA0
160          X SEA3/SO
             A=EXP(-SO)
             B=1.-2./(LT*LT)
             P1=.45645*A*(1.-4)*(1.-EXP(-2./R))
             P2=.9/;45D*A*(1.-A)*(1.-EXP(-6./B))
165          X=2.
             Y=P1/P2
       17    T1=EXP(-2./K)
             T2=1.-T1
             T3=EXP(-6./K)
             T4=1.-T3
170          T5=(-2.*T1*T4+.*T3*T21/(K*X*T4*T4)
```

```
175        T6=(T2/T4-Y)/T5
           X=X-T6
           IF (ABS(T6).GT.1.E-5) GO TO 17
           M2=SQRT(X)
           M1=P1/T2

     C
     C     TRANSMISSION
           T=TC*TM*TBE*TEA
180        P=T*PI

     C
     C     JITTER
           TH=SQRT(THTR**2+THSV**2+THBS**2+THE**2+(THI**2+THAA**2)/(MAG**2))
           WRITE (6,23)
           WRITE (6,24)
185        WRITE (6,25) BLK,ONE,SI,ZR,BLK,ONE,SAW,ZR,BLK,TC,ZR,BLK,HM(ITYPEM),
          (TM,SM,LM,HM(ITYPE9),TRE,SBE,LBE,HEA(ITYPEA),TEA,SEA,DLI,BLK,T,S,LT
           WR=1.+(3.1+159*DB/(4.*WL*R2))**2
           WR=SQRT(WR)
20         XM2=M2
190        M2=WR*M2
           WRITE (6,26) DB,P,M1,XM2,WR,M2
           WRITE (6,27) TH,R2
           RETURN

     C
18   FORMAT(10X,30(1H*),*INPUT TO OPTICAL TRAIN*,30(1H*))
19   FORMAT(20X,*LASER BEAM DIAMETER    *,    G12.4,* METERS*/
1          20X,**LASER POWER           *,0PG12.4,* WATTS    */
2          20X,**WAVELENGTH            *,  E12.4,* METERS*/
3          20X,**OBSCURATION           *,.0PG12.4,*       */
4          20X,**BEAM QUALITY          *,.G12.4,*         */
5          20X,**PULSE LENGTH          *,.G12.4,* SECONDS */
6          20X,**PHASE FRONT CURVATURE *,   G12.4,* METERS*/
7          20X,**JITTER                *,.0PG12.4,* RADIANS */
8          20X,**INTENSITY FLUCTUATIONS*,.G12.4,* PEAK-TO-PEAK*/
20   FORMAT(20X,*SCALE SIZE OF FLUCTUATIONS *,.G12.4,* L/WT
X          20X,**TYPE OF AEROWINDOW     *,.A9/
1          20X,**AEROWINDOW DELTA RHO/RHO *,.G12.4,*        */
2          20X,**RHO/RHO REF            *,.G12.4,*        *
3          20X,**DISTANCE TO CLIPPER    *,   G12.4,* METERS*/
4          20X,**CLIPPER DIAMETER       *,.G12.4,* METERS*/
5          20X,**NUMBER OF MIRRORS      *, I2, *        */
6          20X,**REFLECTIVITY           *,.0PG12.4,*        */
7          20X,**FABRICATION ERROR      *,.G12.4,* VIS. LAMBDAS*/
8          20X,**TYPE OF MIRRORS        *,.A8)
21   FORMAT(20X,*DISTANCE BETWEEN MIRRORS *,   G12.4,* METERS*/
1          20X,**TELESCOPE MAGNIFICATION *,.0PG12.4,*        */
3          20X,**TELESCOPE DIAMETER     *,   G12.4,* METERS*/
4          20X,**TELESCOPE TYPE         *,.A8. *        */
2          20X,**TYPE OF EXIT APERTURE  *,.A8. *        */
5          20X,**EXIT APERTURE LENGTH   *,.G12.4,* METERS */
6          20X,**ABSORPTION COEFFICIENT *,.0PG12.4,* METERS-)
X          20X,**TEMPERATURE FLUCTUATION *,.G12.4,* DEG K  */
7          20X,**INPUT AREA/ BEAM AREA   *,.G12.4,*        *;
22   FORMAT(20X,*TRACKER JITTER         *,.G12.4,* RADIANS */
1          20X,**BORE-SIGHT JITTER      *,.G12.4,* RADIANS */
2          20X,**SERVO JITTER           *,.G12.4,* RADIANS */
3          20X,**OPTICAL FIGURE JITTER  *,.G12.4,* RADIANS *)
```

```
SUBROUTINE OPTRAIN     73/74     OPT=0     TRACE                          FTN 4.0+P357          04/06/75   13.10.03.     PAGE     5

23    FORMAT(1H1,10X,30(1H*),*OPTICAL TRAIN OUTPUT*,30(1H*)//)                                      221
24    FORMAT(23X*SOURCE              *,8X,*TRANSMISSION SIGMA    L/WT    *)                          222
25    FORMAT(20X,*INPUT BEAM         *,A8,2X,F8.4,2X,2F8.4/                                          223
1          20X,*AERODYNAMIC WINDOW *,A9,2X,F8.4,2X,2F8.4/                                            224
2          20X,*BEAM CLIPPER       *,A8,2X,F8.4,2X,2F8.4/                                            225
3          20X,*MIRRORS            *,A8,2X,F8.4,2X,2F8.4/                                            226
4          20X,*BEAM EXPANDER      *,A8,2X,F8.4,2X,2F8.4/                                            227
5          20X,*EXIT APERTURE      *,A8,2X,F8.4,2X,2F8.4/                                            228
6          20X,*TOTALS             *,A8,2X,F8.4,2X,2F8.4)                                            229
26    FORMAT(20X,*TRANSMITTED BEAM DIAMETER*,F8.4,* METERS*/                                         230
1          20X,*TRANSMITTED POWER*,G12.4,* WATTS*/                                                   231
2          20X,*BEAM QUALITY BEFORE ACCOUNTING FOR DIVERGENCE*/                                      232
3          3IX,*M1 =*,F8.4,4X,*M2 =*,F8.4/                                                           233
4          20X,*EFFECT OF BEAM DIVERGENCE ON WAIST*,G12.4/                                           234
X          2CX,*FINAL BEAM SPREAD PARAMETER, M2*,G12.4)                                              235
27    FORMAT(20X,*TOTAL BEAM JITTER*,G12.4,* RADIANS*/                                               236
X          20X,*PHASE FRONT CURVATURE*, G12.4,* METERS*///)                                          237
END                                                                                                 238
```

```
                SUBROUTINE ATM                                                  ATM     2
        C                                                                       ATM     3
        C       ATM SETS UP THE VARIABLES FOR THE FOUR MAIN PROPAGATION SUBROUTINE ATM   4
        C       IT CALCULATES THE INITIAL STEP OF ALL TYPES OF PROPAGATION AND  ATM     5
        C       REFINES THE ESTIMATES FOR THE REVERSE CALCULATIONS UNTIL THEY ARE ATM    6
        C       WITHIN THE SPECIFIED RANGE.                                     ATM     7
                                                                                ATM     8
                LOGICAL CPHI,EQUAL,ERR,PRINT                                     ATM     9
                INTEGER TYPED(4),TYPEE(4)                                        ATM    10
                INTEGER BEAM,DEBUG,FINAL,OUT,PO,PHOP,TYPE,WTHR                   ATM    11
                REAL I,IHD,IOLD,KAS,KDL,KIP,L,LAMDA,LT2,LT23O,M,MSO,NBAR,NU      ATM    12
                REAL KI,IP,M2,MI                                                ATM    13
                                                                                ATM    14
        C       COMMON /ERROR/ ERR                                              ATM    15
                COMMON /ATMIN/ M,OI,PHOP,SIGLF,SIGHF,WTHR,M1,M2                  ATM    16
                COMMON /MESH/ XPKAS,ZPREV,XN,AREA                               ATM    17
                COMMON /ALFDTA/ DUMMY(4),PLINE(3),ABL,ABE,SCL,SCE               ATM    18
                COMMON /ATMS/ REAM,FL,GL,HTM,IBD,L,LAMDA,NSTEP,PHI              ATM    19
                COMMON /IN/ COEFP,HOM,HI                                        ATM    20
                COMMON /INS/ DEBUG,ITYPE,OUT,PI,PO                              ATM    21
                COMMON /INT/ PD                                                 ATM    22
                COMMON /SATM/ COEF1,COEF2,COEF3,COSPHI,EQUA.,FINAL,FIVE3,FIVE9,G2, ATM  23
               1G3,G4,G5,HTF,I,IFLAG,KAS,KIP,LT2,LT23O,MSO,VSM1,PI,PO,PRINT,ROSO,R ATM 24
               210,SIGASO,SIGHSO,SIGM4T,SIGSO,HOLD                              ATM    25
                COMMON /ALFA/ LAM,RH                                            ATM    26
                COMMON /CNVW/ IM                                                ATM    27
                COMMON /X/ CHI,OMEGA,VP,VPSC,VXB                                ATM    28
                                                                                ATM    29
        C       EXTERNAL ALFAEX,CMSO                                            ATM    30
                NAMELIST /USPEC/ PLINE,ABL,ABE,SCL,SCE                          ATM    31
                                                                                ATM    32
        C       DATA PI/3.14159/                                               ATM    33
                DATA TYPED/SHABOVE,SHBELOW,SHABOVE,SHBELOW/                      ATM    34
                DATA TYPEE/SHABOVE,SHRELOW,SHBELOW,SHABOVE/                      ATM    35
                                                                                ATM    36
        C       SELECT LAMS                                                     ATM    37
                LAM=1                                                           ATM    38
                PLINE(1)=.338                                                   ATM    39
                PLINE(2)=.32                                                    ATM    40
                PLINE(3)=.342                                                   ATM    41
                ABL=ABE=SCL=SCE=0.                                              ATM    42
                IF (LAMDA.GT.0.) GO TO 2                                        ATM    43
                READ (5,USPEC)                                                  ATM    44
                IF (ABL.NE.0.) LAM=4                                            ATM    45
              2 LAMDA=ABS(LAMDA)                                                ATM    46
                TEMP=1./(PLINE(1)+PLINE(2)+PLINE(3))                            ATM    47
                DO 1 III=1,3                                                    ATM    48
              1 PLINE(III)=PLINE(III)*TEMP                                      ATM    49
                WRITE (6,44) PLINE(1),PLINE(2),PLINE(3),ABL,ABE,SCL,SCE         ATM    50
                IF (LAM.EQ.4) GO TO 3                                           ATM    51
                IF (LAMDA.EQ.3.8E-6) LAM=2                                      ATM    52
                IF (LAMDA.EQ.0.5E-6) LAM=3                                      ATM    53
        C                                                                       ATM    54
        C       COLLIMATED OR FOCUSED BEAM                                      ATM    55
        C       (FOCUSED)                                                       ATM    56
              3 G4=0.                                                           ATM    57
                G5=1.                                                           ATM    58
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```
          IF (REAM.EQ.1) GO TO 4                                    ATM    59
C         (COLLIMATED)                                              ATM    60
          G5=0.                                                     ATM    61
          G4=1.                                                     ATM    62
C                                                                   ATM    63
C         SET CONSTANTS AND VARIABLES                               ATM    64
4         G3=1.-.R65*M1                                             ATM    65
          COEF2=PT/PI                                               ATM    66
          COEF3=.R65*M1*PT                                          ATM    67
          EXPKAS=1.                                                 ATM    68
          FINAL=2                                                   ATM    69
          FIVE3=5./3.                                               ATM    70
          FIVE9=5./9.                                               ATM    71
          HOM=HOM+GL                                                ATM    72
          HTM=HTM+GL                                                ATM    73
          IFLAG=1                                                   ATM    74
          IW=WTHR**2                                                ATM    75
          KAS=0.                                                    ATM    76
          KOUNT=0                                                   ATM    77
          LCOUNT=0                                                  ATM    78
          M=M2                                                      ATM    79
          MSQ=M**4                                                  ATM    80
          OIM=1.05*OI                                               ATM    81
          OIL=.95*OI                                                ATM    82
          PO=1                                                      ATM    83
          ROSQ=RO*RO                                                ATM    84
          RIG=RO*10.                                                ATM    85
          SIGSQ=SIGLF**2+SIGHF**2                                   ATM    86
          ZPREV=0.                                                  ATM    87
          SIGMAH=0.3183*M2*LAMDA/(RO**2.)                           ATM    88
          SIGASQ=SIGMAR*SIGMAR                                      ATM    89
          SIGMA=SQRT(SIGASO+SIGSO)                                  ATM    90
          SIGASQ=SIGMA*SIGMA                                        ATM    91
          SIGMAT=0.                                                 ATM    92
          Z=0.                                                      ATM    93
          IF (ITYPE.NE.5) GO TO 5                                   ATM    94
C                                                                   ATM    95
C         CALCULATE L FOR REVERSE PROPAGATION--OI AND PT KNOWN      ATM    96
          FL=L                                                      ATM    97
          IF (L.GT.0.) GO TO 5                                      ATM    98
          NU=.865*PT*M1-PI*G4*ROSO*OI                               ATM    99
          L=SORT(NU/(4.*PI*OI*SIGASO))                              ATM   100
          IF (DEBUG.EQ.2) WRITE (6,33) NU,L                         ATM   101
          IF (L.LT.R10) L=100.                                      ATM   102
          FL=L                                                      ATM   103
C                                                                   ATM   104
C         CALCULATE PHI OR HTM                                      ATM   105
5         CPHI=.FALSE.                                              ATM   106
          IF (PHI.LT.0.) GO TO 6                                    ATM   107
          COSPHI=COS(PHI)                                           ATM   108
          HTM=MOM+L*COSPHI                                          ATM   109
          GO TO 7                                                   ATM   110
6         CPHI=.TRUE.                                               ATM   111
          HO=HTM-HOM                                                ATM   112
          HOP=AHS(HO)                                               ATM   113
          NHO=1                                                     ATM   114
          IF (HOP.NE.HO) NHO=-1                                     ATM   115
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115          IF (L.LT.HDP) HD=L*NHD                                      ATM   116
             COSPHI=HD/L                                                 ATM   117
             PHI=ACOS(COSPHI)                                            ATM   118
      7      VPSC=VP*((SIN(PHI)*SIN(CHI))**2+COSPHI**2)                  ATM   119
             IF (DEBUG.EQ.2) WRITE (6,34) HOM,HTM,PHI                    ATM   120
120          HTF=3.281*HTM                                               ATM   121
             LT2=L**2.                                                   ATM   122
             LT2SQ=LT2*LT2                                               ATM   123
             IF (HOM.GT.1E5.AND.HTM.GT.1E5) NSTEP=1                      ATM   124
             NSW1=NSTEP-1                                                ATM   125
125   C                                                                  ATM   126
      C      GAUSSIAN OR PLANE WAVE                                      ATM   127
      C                                                                  ATM   128
             G2=6.54                                                     ATM   129
130          IF (PROP.EQ.2) G2=3.5A                                      ATM   130
             IF (PROP.EQ.3) G2=4.9                                       ATM   131
             IF (OUT.EQ.2) WRITE (6,49)                                  TCP    23
      C                                                                  ATM   132
      C      DECIDE WHICH TYPE OF CALCULATIONS TO DO                     ATM   133
      C                                                                  ATM   134
             IF (HOM.LT.1E5) GO TO 9                                     ATM   135
135          IF (HTM.LT.1E5) GO TO 8                                     ATM   136
             TYPE=1                                                      ATM   137
             GO TO 11                                                    ATM   138
      8      TYPE=3                                                      ATM   139
             GO TO 11                                                    ATM   140
140   9      IF (HTM.LT.1E5) GO TO 10                                    ATM   141
             TYPE=4                                                      ATM   142
             GO TO 11                                                    ATM   143
      10     TYPE=2                                                      ATM   144
145   11     WRITE (6,35) TYPED(TYPE),TYPEE(TYPE)                        ATM   145
      C                                                                  ATM   146
      C      PROPAGATION OR REVERSE PROPAGATION                          ATM   147
      C                                                                  ATM   148
             IF (ITYPE.NE.5) GO TO 12                                    ATM   149
      C      REVERSE PROPAGATION--OI AND PT KNOWN                        ATM   150
150          FINAL=1                                                     ATM   151
      C                                                                  ATM   152
      C      REGULAR PROPAGATION                                         ATM   153
      C                                                                  ATM   154
      12  C  COMPUTE STARTING VALUES OF AREA AND INTENSITY               ATM   155
155          AREA=PI*ROSQ                                                ATM   156
             I=PT/AREA                                                   ATM   157
             IP=2.312*I                                                  ATM   158
             EXPKAS=1.                                                   ATM   159
             KAS=0.                                                      ATM   160
160          SIGMAT=0.                                                   ATM   161
             PRINT=.FALSE.                                               ATM   162
             IF (OUT.EQ.2.AND.(FINAL.EQ.2.OR.DEBUG.EQ.2)) PRINT=.TRUE.   ATM   163
             IF (PRINT) WRITE (6,36) Z,HOM,SIGMAT,SIGTST,EXPKAS,AREA,I,IP ATM   164
      C                                                                  ATM   165
             GO TO (13,14,15,16), TYPE                                   ATM   166
165   13     CALL AA (HOM)                                               ATM   167
             GO TO 4A                                                    ATM   168
      14     CALL HH (HOM)                                               ATM   169
             GO TO 4B                                                    ATM   170
      15     CALL AH (HOM)                                               ATM   171
170          GO TO 4B
      16     CALL HA (HOM)
```

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      C
      4A    IF (ERR) RETURN                                              ATM 172
      C                                                                  ATM 173
            IF (XN.LT.1.E-8) RETURN                                      ATM 174
            IF (TYPE.EQ.1) RETURN                                        ATM 175
            IF (ITYPE.EQ.5) GO TO 22                                     ATM 176
      C                                                                  ATM 177
      C     COMPUTE AND PRINT DISPLACEMENT, ECCENTRICITY AND ISO-INTENSITY ATM 178
      C     CONTOUR DATA.                                                ATM 179
      C                                                                  ATM 180
            AF=.7071067H*ROLO                                           ATM 181
            PTOTAL=PT*XPKAS*(1.-G3)                                     ATM 182
            ETA=ROLD/HO                                                 ATM 183
            ANOM=3.1415926*AF*AF/KIP                                    ATM 184
            ECC=0.3+0.7*KIP                                             ATM 185
            CISP=(-0.692)*SQRT(0.478864-2.6666667*ALOG(KIP))            ATM 186
            DISP=AF*(ETA**(-.29))*DISP                                  ATM 187
            IF (PD .EQ. 0.) WRITE (6,49)                                ATM 188
            WRITE (6,42) DISP,ECC                                       TCP  24
            GAMMA=1.0                                                   ATM 189
            DGAM=0.1                                                    ATM 190
            DO 17 KGAM=1,9                                              ATM 191
            GLN/A=GAMMA-DGAM                                            ATM 192
            AREA=(-ANGM)*ALOG(GAMMA)                                    ATM 193
            POWER=PTOTAL*(1.-GAMMA)                                     ATM 194
            AVGI=POWER/AREA                                             ATM 195
            WRITE (6,43) GAMMA,AREA,POWER,AVGI                          ATM 196
      17    CONTINUE                                                     ATM 197
      C                                                                  ATM 198
      C     BREAKDOWN POWER AND OPTIMUM POWER CALCULATIONS               ATM 199
      C                                                                  ATM 200
            IF (PD .NE. 0.)WRITE (6,49)                                 ATM 201
            PRD = IHD * PT * KIP / (2.312 * I)                          TCP  25
            PRINT 45, IHD,P9D                                           ATM 202
            PMAX=PT*5.54/XN                                             ATM 203
            XI=I*1.205/(XN*KIP)                                         ATM 204
            IF (PMAX.LE.PHD) GO TO 18                                   ATM 205
            PMAX=PHD                                                    ATM 206
            XI=IHD                                                      ATM 207
      18    PRINT 32, XI,PMAX                                            ATM 208
      C                                                                  ATM 209
      C     EFFECT OF POWER VARIATIONS                                   ATM 210
      C                                                                  ATM 211
            DP=PT*0.1                                                    ATM 212
            DN=XN*0.1                                                    ATM 213
            PP=0.                                                        ATM 214
            YN=0.                                                        ATM 215
            PTOT=I/(KIP*PT)                                             ATM 216
            DO 20 III=1,20                                              ATM 217
            PP=PP+DP                                                     ATM 218
            IF (PP.GT.P9D) GO TO 21                                     ATM 219
            YN=YN+DN                                                     ATM 220
            ZZ=K(HEAM*YN)                                               ATM 221
            ZN=I*ZZ*YN/(XN*KIP)                                         ATM 222
            ZXXX=ZN*2.312                                               ATM 223
            FACTON=CI/ZXXX                                              ATM 224
            IF ((FACTON.LT.1).AND.(FACTOR.GT.0.)) GO TO 19              ATM 225
                                                                        ATM 226
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```
                 PUSE=0.                                                       ATM    227
                 AUSE=0.                                                       ATM    228
                 GO TO 20                                                      ATM    229
      19         PUSE=PTOT*PP*(1.-FACTOR)                                      ATM    230
                 AUSE=-0.5*AREA*ALOG(FACTOR)/ZZ                                ATM    231
      20         PRINT 46, PP,ZN,PUSE,AUSE                                     ATM    232
      21         PRINT 47, OI                                                  ATM    233
                 RETURN                                                        ATM    234
      C                                                                        ATM    235
      C      REFINEMENT LOOP FOR ITYPE 5                                       ATM    236
      C                                                                        ATM    237
      22         LCOUNT=LCOUNT+1                                               ATM    238
                 IF (LCOUNT.GT.20) GO TO 31                                    ATM    239
                 IF (FINAL.EQ.2) RETURN                                        ATM    240
      C                                                                        ATM    241
      C      SELECTION OF NEXT FOCAL LENGTH                                    ATM    242
                 XK=0.7                                                        ATM    243
                 RAT=1/OI                                                      ATM    244
                 IF (RAT.LT.0.45.OR.RAT.GT.2.22) GO TO 26                      ATM    245
                 IF (RAT.LT.0.62.OR.RAT.GT.1.6) GO TO 25                       ATM    246
                 IF (RAT.LT.0.8.OR.RAT.GT.1.25) GO TO 24                       ATM    247
                 IF (RAT.LT.0.91.OR.RAT.GT.1.1) GO TO 23                       ATM    248
                 XK=1.0                                                        ATM    249
      23         GO TO 26                                                      ATM    250
                 XK=0.95                                                       ATM    251
                 GO TO 26                                                      ATM    252
      24         XK=0.9                                                        ATM    253
                 GO TO 26                                                      ATM    254
      25         XK=0.8                                                        ATM    255
      26         FL=FL*XK*SQRT(RAT)                                            ATM    256
                 IF (FL.GE.R10) GO TO 27                                       ATM    257
                 KOUNT=KOUNT+1                                                 ATM    258
                 IF (KOUNT.GT.2) GO TO 30                                      ATM    259
                 FL=100.                                                       ATM    260
      27         L=FL                                                          ATM    261
                 LT2=L*2                                                       ATM    262
                 LT2SQ=LT2*LT2                                                 ATM    263
      C                                                                        ATM    264
      C      RECALCULATE PHI OR MTM                                            ATM    265
                 IF (CPHI) GO TO 28                                            ATM    266
                 MTM=MCM*L*COSPHI                                              ATM    267
                 MTM=MTM+GL                                                    ATM    268
                 GO TO 29                                                      ATM    269
                 HD=MTM-MOM                                                    ATM    270
                 MDP=ABS(HD)                                                   ATM    271
                 NHD=1                                                         ATM    272
                 IF (HDP.NE.HD) NHD=-1                                         ATM    273
                 IF (L.LT.HDP) HD=L*NHD                                        ATM    274
      28         COSPHI=HD/L                                                   ATM    275
                 PHI=ACOS(COSPHI)                                              ATM    276
      29         IF (DEBUG.EQ.2) WRITE (6,37) FL,MTM,PHI                       ATM    277
                 IF (I.LT.OIL.OR.I.GT.OIH) GO TO 12                            ATM    278
                 WRITE (6,36) L                                                ATM    279
                 FINAL=2                                                       ATM    280
                 GO TO 12                                                      ATM    281
      C                                                                        ATM    282
      C      PAGE TOO SMALL                                                    ATM    283
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          30    WRITE (6,39)
                ERR=.TRUE.                                                     ATM    284
                RETURN                                                         ATM    285
                                                                               ATM    286
          C           TOO MANY TIMES THROUGH THE LOOP                          ATM    287
          C     31    WRITE (5,40) LCOUNT,FL,I,OI                              ATM    288
          31                                                                   ATM    289
                ERR=.TRUE.                                                     AT     290
                RETURN                                                         ATM    291
                                                                               ATM    292
          C                                                                    ATM    293
          C                                                                    ATM    294
          32    FORMAT (30X,*MAXIMUM INTENSITY ON TARGET =*,1PE10.2,10X,*ACHIEVED   ATM    295
                1AT TELESCOPE POWER =*. E10.2,///,56X,*POWER RANGE AVAILABLE*,//,   ATM    296
                2 T10.                                       *TELESCOPE PO    ATM    297
                2HER*,T40,*INTENSITY*,T70,*USEFUL POWER*,T100,*OVER AREA*/T10,*(WAT   ATM    298
                3TS)*,T40,*(WATTS/M**2),T70,*(WATTS)*,T100,*M(M**2))           ATM    299
          33    FORMAT (//10X,*FOR ITYPE 5.  NU =*,1PE12.5,*,  L =*,E12.5)     ATM    300
          34    FORMAT (//10X,6HMOM =*,E12.5,8H, MTM =*,E12.5,8H, PHI =*,E12.5)    ATM    301
          35    FORMAT (//10X,24HCALCULATIONS FOR ORIGIN ,A1,19H 100 KM AND TARGET   ATM    302
                1 ,A5,8H 100 KM.)                                             ATM    303
          36    FORMAT (//,7X,*DISTANCE*,8X,*HEIGHT*,7X,*SIGMAT-LT*,6X,*SIGMAT-ST*,   ATM    304
                18X,  *EXPKAS*. 10X,*AREA*,8X,*INTENSITY*,8X,*IPEAK*,//,8X,*METERS*,   ATM    305
                2,9X,*METERS*,8X,*RADIANS*,8X,*RADIANS*,23X,  *METERS*3M**2,5X,       ATM    306
                3  *WATTS/M**2, 5X,*WATTS/M**3M**2,//,1X,1P6E15.4)            ATM    307
          37    FORMAT (//10X,13HDEFINED FL =*,E12.5,8H, HT% =*,E12.5,8H, PHI =  .E   ATM    308
                112.5)                                                         ATM    309
          38    FORMAT (10X,19HTARGET RANGE (L) =--,1PE10.3,7H METERS/)        ATM    310
          39    FORMAT (//10X,23HDEFINED RANGE TOO SMALL)                      ATM    311
          40    FORMAT (//10X,*ITYPE 5 HAS NOT CONVERGED AFTER*,13,         11M I   ATM    312
                1TERATIONS/10X-5HFL =*,E12.5,6H, I =*,E12.5,7H, OI =*,E12.5)   ATM    313
          42    FORMAT(//10X,*DISPLACEMENT =*,F6.3,* METERS*,10X,*ECCENTRICITY =*,   ATM    314
                1,F6.3,//,5X,*I/IPEAK*,10X,    *AREA*,8X,*CUMULATIVE*,7X,  *AVERAG   ATM    315
                1E*,/,37X,  *CONTOUR*,7X,*(METER*,4M**2),7X,  *POWER*,9X,*INTENSIT   ATM    316
                2Y*,/)                                                         ATM    317
          43    FORMAT (35X,F6.1,4X,1P3E15.3)                                 ATM    318
          44    FORMAT(/,10X,*PLINE (1) =*,1PE10.2,3X,*PLINE (2) =*,E10.2,3X,   ATM    319
                1*PLINE (3) =*,E10.2,/,10X,*ABL =*,E10.2,9X,*ABE =*,E10.2,9X.   ATM    320
                2*SCL =*,E10.2,9X,*SCE =*,E10.2,//)                           ATM    321
          45    FORMAT(//30X,*BREAKDOWN INTENSITY        =*,1PE10.2,10X,  *ACHIEV   TCP    26
                1ED AT TELESCOPE POWER =*,E10.2)                              ATM    323
          46    FORMAT (T10,1PE10.3,T40,E10.3,T70,E10.3,T100,E10.3)           ATM    324
          47    FORMAT (//10X, *USEFUL INTENSITY =*,1PE10.3,*WATTS/M*,3M**2)   ATM    325
          49    FORMAT (1H1)                                                  TCP    27
                END                                                           ATM    326
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```
      SUBROUTINE AA (HOM)
C
C     CALCULATIONS FOR ORIGIN AND TARGET ABOVE 100 KM
C
      LOGICAL EQUAL,EXP,PRINT
      INTEGER PERM,DEBUG,FINAL,OUT,PO
      REAL I,IAU,KAS,KIP,L,LAMDA,LT2,LT2SO,MSO
C
      COMMON /MESH/ XTRA(3),AREA
      COMMON /ERROR/ ERR
      COMMON /ATMS/ PERM,FL,GL,MTM,IRD,L,LAMDA,NSTEP,PHI
      COMMON /INS/ DEBUG,ITYPE,OUT,PT,PO
      COMMON /SATM/ COEF1,COEF2,COEF3,CCSPHI,EQUAL,FINAL,FIVE3,FIVE9,G2,
     1C3,G4,G5,MTF,I,IFLAG,KAS,KIP,LI2,LT2SO,MSO,NSM1,PI,PO,PRINT,MRSO,R
     210,SIG4SO,SIG4SO,SIGMAT,SIGSO,KOLD
C
C     CALCULATE RADIUS, AREA, AND INTENSITY
      RSO=LT2SO*SIG4SO
      R=SQRT(RSO)
      AREA=PI*RSO
      I=COEF3/AREA
      IF (FINAL.NE.2.AND.DEBUG.EQ.1) RETURN
C
C     WRITE RESULTS
      ROLD=R
      IF (OUT.EQ.1) GO TO 1
      WRITE (6,2) L,MOM,I,AREA,R
      RETURN
    1 WRITE (6,3) MTM,MTF,L,R,AREA,I
      RETURN
C
C
    2 FORMAT (10X,12HABOVE 100 KM/1X,1P2E15.4,5X,2H0,,8X,3E15.4,5X,10H1.
     10003E+0C/)
    3 FORMAT (//10X,23HTARGET ALTITUDE (MTM) =,1PE10.3,9H METERS 1.E10.3
     1,5H FEET)/10X,42HTARGET RANGE (L)                =,69.2,7H
     2M METERS,12X,29HRADIUS WITHOUT BLOOMING (R) =,CPF7.2,7H METERS/10X
     3,42HAREA WITHOUT BLOOMING (AREA)    =,1PE10.3,10H METERS= =,
     4*2.8X,29HTARGET PLANE INTENSITY (I) =,E11.4,11H WATTS/M**2/)
      END
```

```fortran
      SUBROUTINE AB (HOW)                                                    2
C                                                                            3
C     CALCULATIONS FOR ORIGIN ABOVE 100 KM AND TARGET BELOW 100 KM           4
C                                                                            5
      REAL I,L,L1,L2                                                         6
      REAL IP                                                                7
      LOGICAL PRINT                                                          8
      COMMON /ATMS/ HEAM,FL,GL,HTM,IPD,L,LAMDA,NSTEP,PHI                     9
      COMMON /INS/ DEBUG,ITYPE,OUT,PT,R0                                    10
      COMMON /SATM/ COEF1,COEF2,COEF3,COSPHI,EQUAL,FIVE3,FIVE9,G2,          11
     1G3,G4,G5,HTF,I,IFLAG,KAS,KIP,LT2,LT2SO,MSO,NSM1,P1,PO,PRINT,R0SO,R    12
     210,SIG4SO,SIG8SO,SIGMAT,SIGSO,ROLD                                    13
      COMMON /MESH/ EXPXAS,L1,N1,AREA                                       14
      L1=(1E5-HOM)/COSPHI                                                   15
      L2=L-L1                                                               16
C                                                                           17
C     ABOVE 100 KM                                                          18
C                                                                           19
      RSO=R0SO                                                              20
      IF (HEAM.EQ.1) RSO=(R0*L2/L)**2                                       21
      RSO=RSO+4.*L1*L1*SIGASO                                               22
      R=SQRT(RSO)                                                           23
      AREA=PI*RSO                                                           24
      L1=(1E5-HOM)/COSPHI                                                   25
      L2=L-L1                                                               26
C                                                                           27
C     ABOVE 100 KM                                                          28
C                                                                           29
      RSO=R0SO                                                              30
      IF (HEAM.EQ.1) RSO=(R0*L2/L)**2                                       31
      RSO=RSO+4.*L1*L1*SIGASO                                               32
      R=SQRT(RSO)                                                           33
      AREA=PI*RSO                                                           34
      IPT/AREA                                                              35
      IP=IP*2.312                                                           36
      IF (PRINT) WRITE (6,1) L1,AREA,I,IP                                   37
      HOLD1=FL                                                              38
      FL=HOLD1                                                              39
      HOLD2=R0SO                                                            40
      HOLD3=L                                                               41
      FL=L2                                                                 42
      L=L2                                                                  43
      R0SO=RSO                                                              44
C                                                                           45
      CALL ER (1.E5)                                                        46
      FL=HOLD1                                                              47
C                                                                           48
      R0SO=HOLD2                                                            49
      L=HOLD3                                                               50
      RETURN                                                                51
C                                                                           52
C                                                                           53
    1 FORMAT (6X,*ABOVE 100 KM*,/,1X,1PE15.4,15.4,15.4,00,.3000E-00,.0X)    54
     1E0,.*,13X,*1.0000E-00*,.3E15.4,(//)                                   55
      END                                                                   56
```

```
      SUBROUTINE BA (MOM)                                              BA    2
C                                                                      BA    3
C     CALCULATIONS FOR ORIGIN BELOW 100 KM, AND TARGET ABOVE 100 KM    BA    4
C                                                                      BA    5
      COMMON /XY/ SIGTST                                               BA    6
      COMMON /MESH/ EAP/AS,ZPPEV,NS,AREA                               BA    7
      INTEGER DEBUG,FINAL,OUT                                          BA    8
      REAL I,KIP,L,LT2,L1,L2                                           BA    9
      REAL IP                                                          BA   10
      COMMON /ATMS/ REAP,FL,GL,MTM,IRD,L,LAMDA,NSTEP,PHI               BA   11
      COMMON /IOS/ DEBUG,ITYPE,OUT,PT,P0                               BA   12
      COMMON /SAT/ COEF1,COEF2,COEF3,COSPHI,EQUAL,FINAL,FIVE0,FIVE0,G2, BA  13
     1G3,G4,G5,HIF,I,IFLG,TS,KIP,LT2,LT2SO,NSO,NSY1,P1,P0,PRINT,ROSO,R BA   14
     210,SIGASO,SIG4S,SIG4AT,SIGSO,ROLD                                BA   15
C                                                                      BA   16
      L1=(1E5-HOM)/COSPHI                                              BA   17
      L2=L-L1                                                          BA   18
C                                                                      BA   19
C     HEL04 100 KM                                                     BA   20
C                                                                      BA   21
      MOLD1=L                                                          BA   22
      MOLD2=MTM                                                        BA   23
      L=L1                                                             BA   24
      MTM=1.E5                                                         BA   25
      WRITE (5,3)                                                      BA   26
C                                                                      BA   27
      CALL 99 (MOM)                                                    BA   28
      L=MOLD1                                                          BA   29
C                                                                      BA   30
      MTM=MOLD2                                                        BA   31
C                                                                      BA   32
C     ABOVE 100 KM                                                     BA   33
C                                                                      BA   34
      DELT2=SQRT(SIGASO+SIGTSO)                                        BA   35
      AREA=PI*R*2                                                      BA   36
      HLBDE4=AREA/KIP                                                  BA   37
      I=COEF3*EXP*AS*KIP/AREA                                          BA   38
      IF (FINAL.NE.2.AND.DEBUG.EQ.0) RETURN                            BA   39
      IP=I*2.312                                                       BA   40
      WRITE (5,4)                                                      BA   41
      IF (OUT.EQ.19 GO TO 1                                            TOP  28
      WRITE (5,2) L,MTM,SIGMAT,SIGTST,EXPKAS,RLAREA,I,IP               TOP  29
      RETURN                                                           BA   44
1     WRITE (5,5) MTM,HIF,SIGMAT,L,SIGTST,EXPKAS,R,KIP,I,AREA,IP,RLAREA BA  45
      RETURN                                                           BA   46
C                                                                      BA   47
C                                                                      BA   48
C                                                                      BA   49
2     FORMAT (//,1X,1PAE15.6)                                          TOP  50
3     FORMAT (///,10X,*BEL.M  100  KM*)                                BA   51
4     FORMAT (///,10X,*ABOVE 100 KM*)                                  BA   52
5     FORMAT (///,1CX,*TARGET ALTITUDE (MTM) *=,1PE10.3,* METERS (*,   BA   53
     1E10.3,* FEET*,4X,*LONG-TERM TURBULENCE (SIGMAT) *=,E10.3,        BA   54
     2* RADIUS=*,/,10X,*TARGET RANGE *L)                               BA   55
```

```
46       RADIANS=./.10X,*LINEAR EFFECTS ON TRANSMISSION (EXPRESS)  *, BA       59
50*F6.3.10X.*RADIUS WITHOUT BLOOMING (R)   *  *F7.3*                    BA       60
5*         METERS*./.10X*                    *.ON-LINEAR EFFECTS       BA       61
OON TRANSMISSION', (C1X)  *=*F6.3*10X.*AVERAGE INTENSITY (I)           BA       62
4=*.1PE11.4*./*/SIIN*./*.3H**2/10X.*AREA WITHOUT BLOOMING (AREA)       BA       63
5     =*.E10.3.* METERS**3H**2,5X*PEAK INTENSITY (IP)                  BA       64
6  =*.E11.4.* WATTS/CM*.3H**2/10X*REA WITH BLOOMING (BLAREA)           BA       65
7      =*.E10.3.* METERS**.3H**2./)                                    BA       66
      END                                                              BA       67
```

```
              SUBROUTINE SB (HOM)
C
C             CALCULATIONS FOR ORIGIN AND TARGET BELOW 100 KM
C
              LOGICAL CNV,GO,E30ED,UNIFRM
              LOGICAL EQUAL,ENG,LESS,PRINT
C
              INTEGER REA,DE,AUG,FINAL,OUT,POST
              REAL L,IMU,KAS,KIP,L,LAMDA,LT2,LT250,N50,N,NAJ,NS,IP,N1,N2,M
C
              COMMON /MESH/ FXP,AS,ZP,HFV,NI,AREA
              COMMON /EQ-CN/ EPN
              COMMON /ATMS/ MEAN,FL,GL,NT4,IMU,L,LAMDA,NS,CP,PHI
              COMMON /INS/ DE,AUG,ITYPE,OUT,PI,FD
              COMMON /SZY/ COEF1,COEF2,COEF3,COSPHI,EQUAL,FINAL,FIVE3,FIVE9,G2,
             1G3,G4,G5,NTF,IFL,G,KAS,KIP,LT2,LT250,N50,SN1,PI,PG,PRINT,RE50,R
             2IG,SIG450,SIG450,SIGN21,SIG50,HOLD
              COMMON /ATPIN/ N,01,PROP,SIGLF,SIGMF,NT43,M1,M2
              COMMON /XY/ SIGISI
C
C             LOGICAL OK
C
              DIMENSION UG10P(5), OG10N(5)
              DIMENSION SVSTSO(50)
C
              DATA OG10P/.4429533,.4325317,.3497048,.2166477,.0745717/
              DATA OG10N/.03333567,.07472567,.1095432,.134634,.1677871/
              DELTAZ=L/NSTEP
C
C             COMPARE STARTING Z WITH R0*10
              DO 1 K=1,N5M1
              KJ=K
              Z=DELTAZ*K
              R-01NT=0.
              IF (Z.GE.P10) GO TO 2
              OK=.TRUE.
              WRITE (6,221) Z,R10
              E0JJ=.TRUE.
              RETURN
C
    2         LESS=.FALSE.
              IF (NTM.LT.NOM) LESS=.TRUE.
              Y=0.
              R-01NT=0.
              OK=.TRUE.
              CALL ALFSET (XLAM,LAM)
              DZ=DELTAZ*0.1
              CM=DZ*COSPHI
              M=0+G-0+0=0.5
              TEMP2=1./FLOAT(NSTEP)
              TEMP4=6.646*6.646/CACA10*0.6
              TEMP7=1.434*(LAMDA/6.2031E9)**1.2
C
C             LINEAR LOOP
C
              DO M J=K,J=1,STEP
              N=J*FLOAT(NSTEP)-J:0*TEMP2
              TEMP1=N,J=N,5*TEMP2
```

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```
                                                              59
      Z=DELTAZ*J                                              60
      ZI=DELTAZ*(J-1)                                         61
      IF (LESS) GO TO 3                                       62
C     SHOOTING UP                                             63
      ML=ZI*COSPHI+HOM                                        64
      MU=Z*COSPHI+HOM                                         65
      MO=U                                                    66
      GO TO 4                                                 67
C     SHOOTING DOWN                                           68
      ML=Z*COSPHI+HOM                                         69
      MU=ZI*COSPHI+HOM                                        70
      MO=L                                                    71
C     TURBULENCE CALCULATIONS                                 72
                                                              73
      ZAL=Z/L                                                 74
      CG10A=0.5*(ML+MU)-GL                                    75
      DG10=ML-MU                                              76
      DO 5 ICG10=1,5                                          77
      TEMP3=SIGP1(ICG10)                                      78
      CG10C=TEMP3+CG10A                                       79
      TEMP3=TEMP3+TEMP2                                        80
      TEMP4=CG10+(1+SIG10)*DELTAZ                             81
      TEMP6=CG5G(CG10A-2SIG10C)*TEMP6                         82
      TEMP5=CG5C(CG10A-2SIG10C)*TEMP6                         83
      PROJTEMP=PROJ*TEMP4+TEMP6                               84
      Y=TEMP6*(TEMP1-TEMP3)+FIVE3-TEMP6*(TEMP1-TEMP2)+FIVE3   85
      R=G11+(1+PROJ*(11)*0.5                                  86
      FAC=1.-0.37*(TEMP4+HOTT/(R0+H0))*0.3333333333           87
      SIGTEU=TEMP/R*1.2                                       88
      SVSTSG(JJ)=SIGISC*(FAC+FAC)*FAC)**2                     89
      SIGTST=SGH+SGS+SG11/2.                                  90
      IF (OMINT) SIGMA1=SQRT(SIGTSG)                          91
                                                              92
      RC=H+S(FL-ZI)/FL                                        93
      RCS=H+C+UC+USG                                          94
      Z=RC+(Z-ZH*EV)**2                                       95
      P=SMT(P4+HCSG+GS+RCSG-Z4+(SIGESG+S(CTSG+SIGSG))         96
      HSG=RCG                                                 97
      DO 6 JJ=1,10                                            98
      FMAX=HCM                                                99
      EMAX=SALF*HAS(IGZ+HH+OF)                                100
      COEF=COEF2*(1.-G3*Z)L)                                  101
      I=COEF*(E4P+LS/H50                                      102
      ID=2.312*I                                              103
      IF (ID.LT.100) GO TO 7                                  104
C     1 GREATER THAN 1 BREAKDOWN, WRITE AND RETURN            105
      WRITE (4,23) Z,IPD                                      106
      ERR=.TRUE.                                              107
      RETURN                                                  108
                                                              109
      AMEL=P1+H50                                             110
C     WRITE OUTPUT                                            111
```

```
115           IF (PRINT) WRITE (6,24) Z,HO,SIGMAT,SIGTST,EXPKAS,AREA,I,IP        B3    116
      8       CONTINUE                                                           B9    117
      C                                                                          83    118
              ROLD=R                                                             B8    119
              FINDTO=1./DELTAZ                                                   B9    120
      C                                                                          89    121
      C       START COMPUTATION OF BLOOMING LOSSES                              B8    122
      C                                                                          B9    123
              ENDED=.FALSE.                                                      B8    124
              CNVRGD=.FALSE.                                                     B9    125
120           HOM=HOM                                                            B9    126
              SIGMAT=SQRT(SIGTSQ)                                                B8    127
      C       CALL ALFSET (NLAM,LAM)                                             B8    128
              TEMP3=(SIGHF+SIGHF)**2+4.*SIG8SQ                                   38    129
      C       TEMP4=G4*R0SQ                                                      E8    130
125           TEMP5=G5*R0SQ                                                      A3    131
              UNIFRM=.FALSE.                                                     B8    132
              RSQ=TEMP4+TEMP5+TEMP3*ZPREV**2                                     B5    133
      C                                                                          B8    134
      C       CALCULATIONS FOR Z = R * 10                                       B8    135
130   C                                                                          83    136
              DZ=P10                                                             B9    137
              HDZ=DZ*0.5                                                         B8    138
              TFDZ=DZ*0.041666666667                                            B8    139
              DZFL=DZ/FL                                                         B8    140
135           TEMP1=DZ*COSPHI                                                    B8    141
              DZSQ=DZ*DZ                                                         B8    142
              TEMP6=G3*DZ/L                                                      85    143
              GPREV=GALTIN(HOM)*ALFFAC(0.,HOM,OK)/(VX(GL,HOM,HOM,PHI,0.,*RSQ)    E8    144
140           Z=DZ                                                               E8    145
              L=HOM+TEMP1                                                        83    146
              G3TRM=1.-TEMP6                                                     83    147
              RC=1.-DZFL                                                         88    148
              RSQ=TEMP4+TEMP5*PC**2+(TEMP3+SVSTSQ(KJ))*(Z+ZPREV)**2             38    149
145           GCURR=GALTIN(H)*ALFFAC(DZ,H,OK)*G3TRM/(VX(GL,H,HOM,PHI,Z)*RSQ)    B8    150
              XCURR=DZSQ*(-0.5*GPREV-(GPREV-GCURR)*0.041666566667)/SQRT(RSQ)    B8    151
              NI=XCURR                                                           B8    152
              G=(GCURR+GPREV)*HDZ                                                B8    153
              GUESS=GCURR+GCURR-GPREV                                            B8    154
150   C                                                                          B8    155
      C       CALCULATIONS FOR NEXT INTERVAL                                     88    156
      C                                                                          83    157
      9       Z=Z+DZ                                                             B8    158
              IF (Z.GE.L) GO TO 16                                               B8    159
155           H=H+TEMP1                                                          89    160
              G3TRM=G3TRM-TEMP6                                                  H9    161
              RC=RC-DZFL                                                         B8    162
      10      TGIND=Z*FINDTO+1.                                                  B8    163
              INDTO=TGIND                                                        9A    164
160           IF (INDTO.GE.NSTEP) INDTO=NSTEP-1                                 B8    165
              SIGTSU=SVSISQ(INDTO)                                               89    166
              SIGTSQ=SIGTSQ+(TGIND-FLOAT(INDTO))*(SVSTSQ(INDTO+1)-SIGTSQ)        89    167
              RSQ=TEMP4+TEMP5*C**2+(TEMP3+SIGTSQ)*(Z+ZPREV)**2                   88    168
165           GNEW=GALTIN(H)*ALFFAC(DZ,H,OK)*G3TRM/(VX(GL,H,HOM,PHI,Z)*RSQ)     A9    169
              IF (ABS(GNEW).LT.1.E-40) GO TO 12                                 B9    170
              OK=.FALSE.                                                         B9    171
170   C                                                                          9E    172
```

```
C     CHECK ACCURACY OF LINEAR EXTRAPOLATION
C
      DEVIAT=ABS((GNEW-GUESS)/GUESS)
      IF (DEVIAT.GT.0.05) GO TO 15
      OK=.TRUE.
      RSOHLD=RSQ
      G=G+GNEW*DZ
      XPREV=XCURR
      XCURR=DZ*(HDZ*GNEW-G)-(GCURR-GNEW)*TFDZ)/SORT(RSQ)
      NI=NI*XCURR
   11 IF (ENDED) GO TO 17
      IF (DEVIAT.LT.0.01) GO TO 12
      GPREV=GCURR
      GCURR=GNEW
      GUESS=GCURR+GCURR-GPREV
      UNIFRM=.TRUE.
      GO TO 9
   12 IF (CNVRGD) GO TO 11
C
C     INCREASE SIZE OF INTERVAL
   13 CONTINUE
      HDZ=DZ
      DZ=DZ+DZ
      UNIFRM=.FALSE.
      IF ((Z+DZ).GE.L) GO TO 14
      TFDZ=TFDZ+TFDZ
      DZFL=DZFL+DZFL
      TEMP1=TEMP1+TEMP1
      TEMP6=TEMP6+TEMP6
      GCURR=GNEW
      GUESS=GCURR+GCURR-GPREV
      GO TO 9
C
C     FINAL INTERVAL
   14 CNVRGD=.TRUE.
      FRACT=(L-Z)/DZ
      IF (FRACT.LT.5.E-4) GO TO 17
      DZ=(L-Z)*0.5
      HDZ=DZ*0.5
      TFDZ=DZ*0.041666666667
      DZFL=DZFL*FRACT
      TEMP1=TEMP1*FRACT
      TEMP6=TEMP6*FRACT
      GUESS=(GNEW-GCURR)*FRACT+GNEW
      GPREV=GNEW+GNEW-GUESS
      GCURR=GNEW
      GO TO 9
C
C     TRY EXPONENTIAL EXTRAPOLATION
   15 DEVIAT=ABS(GCURR**2/(GPREV*GNEW)-1.)
      IF (DEVIAT.LT.0.05) GO TO 19
      IF (DZ.LT.0.01) GO TO 19
      CNVRGD=.FALSE.
      ENDED=.FALSE.
```

```
        C
        C  INTERVAL MUST BE REDUCED
        C
230           MSM=TEMP1                                                         BB
231           G3TUM=G3TPM+TEMP6                                                 BB
232           RC=RC+DZFL                                                        BB
233           Z=Z-DZ                                                            BB
234           DZ=HDZ                                                            BB
235           HDZ=DZ*0.5                                                        BB
236           TFDZ=DZ*0.04166666667                                             BB
237           DZFL=DZFL*0.5                                                     BB
238           TEMP1=TEMP1*0.5                                                   BB
239           TEMP6=TEMP6*0.5                                                   BB
240           GPREV=(GCURR+GPREV)*0.5                                           BB
241           GUESS=GCURR+GCURR-GPREV                                           BB
242           GO TO 9                                                           BB
243     C                                                                       BB
244     16    FRACT=(L-Z+DZ)/DZ                                                 BB
245           IF (FRACT.LT.1.E-3) GO TO 17                                      BB
246           IF (ABS(FRACT-1.).LE.1.E-3) GO TO 10                              BB
247           UNIFRM=.FALSE.                                                    BB
248           DZ=L-Z+DZ                                                         BB
249           HDZ=DZ*0.5                                                        BB
250           TFDZ=DZ*0.04166666667                                             BB
251           DZFL=DZFL*FRACT                                                   BB
252           TEMP1=TEMP1*FRACT                                                 BB
253           TEMP6=TEMP6*FRACT                                                 BB
254           GUESS=(GCURR-GPREV)*FRACT+GCURR                                   BB
255           GPREV=GCURR+GCURR-GUESS                                           BB
256           ENDED=.TRUE.                                                      BB
257           CNVRGD=.TRUE.                                                     BB
258           Z=L                                                               BB
259           GO TO 10                                                          BB
260     17    IF (UNIFRM) NI=NI-0.5*XCURR-(XCURR-XPREV)*0.04166665667           BB
261           NI=R2*COEF2*ABS(NI)                                               BB
262           NI=NI*(77.6+5.A6E-13/LAMDA**2)/(77.6+5.84E-13/1.1236E-10)         BB
263           SIGTSQ=SIGMAT**2                                                  BB
264     C                                                                       BB
265     C  CALCULATION OF INTENSITY WITH BLOOMING                               BB
266     C                                                                       BB
267           XIP=KI(BEAM+ABS(NI))                                             BB
268           I=I+KIP                                                          BB
269           IP=2.312*I                                                        BB
270           HOLDSQ=ROLD*ROLD                                                  BB
271           BLAREA=PI*HOLDSQ/KIP                                              BB
272           IF (FINAL.NE.2.AND.DEBUG.EQ.1) RETURN                             BB
273           IF (OUT.EQ.1) GO TO 18                                            BB
274           WRITE (6.25) NI.KIP.BLAREA.I.IP                                   BB
275           RETURN                                                            BB
276     18    WRITE (6.26) HTM.HTF.SIGMAT.L.SIGTST.EXPKAS.R.KIP.I.AREA.IP.BLAREA BB
277           RETURN                                                            BB
278     19    UNIFKM=.FALSE.                                                    BB
279           OK=.TRUE.                                                         BB
280           GOLD=G/SQRT(RSQMLD)                                               BB
281           RSQ-LC=RSQ                                                        BB
282           G=G+(GNEW-GCURR)*DZ/ALOG(GNEW/GCURR)                              BB
283           TEMP=G/SQRT(RSQ)                                                  BB
```

```
              XPREV=XCURR                                                           BB    287
              XCURR=D7*(GOLD-TEMP)/ALOG(TEMP/GOLD)                                   BB    288
              NI=NI+XCURR                                                           BB    289
              IF (ENDED) GO TO 17                                                   BB    290
 290          IF (DEVIAT.LT.0.01) GO TO 21                                          BB    291
              GPREV=GCURR                                                           BB    292
     20       GCURR=GNEW                                                            BB    293
              GUESS=GCURR+GCURR-GPREV                                               BB    294
              GO TO 9                                                               BB    295
     21       IF (CNVRGD) GO TO 20                                                  BB    296
              GO TO 13                                                              BB    297
     C                                                                              BB    298
     C                                                                              BB    299
     C                                                                              BB    300
 300          FORMAT (59H THE LENGTH OF THE BEAM PATH IS LESS THAN 10 TIMES RO,     BB    301
              1Z = 1PE10.3,7H R10 = E10.3)                                          BB    302
     22       FORMAT(/10X*INTENSITY HAS REACHED BREAKDOWN, Z(J) = *,1PE10.3,* IB    BB    303
              1D = *,E10.3)                                                         BB    304
     23       FORMAT (1X,1PRE15.4)                                                  BB    305
 305          FORMAT (///,* NI = *,1PE12.5,8X,*KIP = *,E12.5,8X,*9LAREA = *,        H3    306
              1E12.5,8X,*IAVL = *,E12.5,8X,*IPEAK = *,E12.5,/)                      BB    307
     24       FORMAT (//,10X,*TARGET ALTITUDE (HTM) =*,1PE10.3,* METERS (*,         BB    308
     25       1E10.3,* FEET)*,9X,*LONG-TERM TURBULENCE (SIGMAT) =*,E10.3,           BB    309
     26       2* RADIANS*,/,10X,*TARGET RANGE (L)                            =*,    B3    310
 310          3E9.2,* METERS*,9X,*SHORT-TERM TURBULENCE (SIGTST)=*, E10.3,          BB    311
              4* RADIANS*,/,10X,*LINEAR EFFECTS ON TRANSMISSION (EXPKAS)      =*,   BB    312
              50PF6.3,19X,*RADIUS WITHOUT BLOOMING (R)       =* ,F7.3,              BB    313
     5*       METERS*,/,10X,                                *NON-LINEAR EFFECTS     BB    314
 315 3 ON TRANSMISSION (KIP) =*,F6.3,19X,*AVERAGE INTENSITY (I)                     TCP   31
     4=*,1PE11.4,* WATTS/M*,3H**2/10X,*AREA WITHOUT BLOOMING (AREA)                 BB    316
     5     =*,E10.3,* METERS*,3H**2,5X*PEAK INTENSITY (IP)                          BB    317
     6 =*,E11.4,* WATTS/M*,3H**2/10X*AREA WITH BLOOMING (BLAREA)                    BB    318
     7     =*,E10.3,* METERS*,3H**2,/)                                              B3    319
              END                                                                   B3    320
```

```
             SUBROUTINE ALFSET (NL,IL)
       C
       C     POWER RATIOS FOR MULTILINE PROPAGATION
       C
             COMMON /ALFDTA/ P(3),RHOFAC,PLINE(3)
             COMMON /ALFA/ LAM,RH
       C
             IF (LAM.EQ.2) GO TO 1
             P(I)=1.
             RETURN
           1 DO 2 I=1,3
           2 P(I)=PLINE(I)
             IF (RH.EQ.0.) RH=1.E-6
             RHOFAC=0.9446*2H-1.
             RETURN
             END
```

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```
              FUNCTION ALFFAC (DZ,H,OK)
C
C         MULTI-LINE POWER LOSSES
C
              LOGICAL  OK
              COMMON /ALFDTA/ P(3),RHOFAC
              COMMON /ALFA/ LAM,RH
              DIMENSION POLD(3)
C
              IF (LAM.EQ.2) GO TO 3
              IF (OK) GO TO 1
              P(I)=POLD(I)
              GO TO 2
    1         POLD(I)=P(I)
    2         TEMP=P(I)*EXP(-ALFAEX(H)*DZ)
              P(I)=TEMP
              ALFFAC=ALFAAB(H)*TEMP
              RETURN
C
    3         IF (OK) GO TO 5
              DO 4 I=1,3
    4         P(I)=POLD(I)
              GO TO 7
    5         DO 6 I=1,3
    6         POLD(I)=P(I)
C
    7         ASSIGN 17 TO J1
              ASSIGN 20 TO J2
              ASSIGN 23 TO J3
              ASSIGN 12 TO J4
    8         SUM=0.
C
              IF (H.GT.13500.) GO TO 11
              IF (H.GT.9500.) GO TO 10
   11         IF (H.GT.5000.) GO TO 9
              ALFAS=3.6E-6*EXP(4.1056*RH-H*0.8333333333E-3)
              GO TO 16
    9         ALFAS=9.3996E-5*EXP(4.1056*RH-H*1.031E-3)
              GO TO 16
   10         ALFAS=4.32E-10*EXP(4.1056*RH)
              GO TO 16
C
C         CALCULATIONS FOR H GREATER THAN 13500 METERS
   11         ATRA=EXP(-ALFAEX(H)*DZ)
   12         GO TO J4(12,14)
              AS=ALFAAH(H)
   13         DO 13 I=1,3
              TEMP=P(I)*XTRA
              P(I)=TEMP
              SUM=SUM+TEMP*AS
   13         ALFFAC=SUM
              RETURN
C
   14         DO 15 I=1,3
              TEMP=P(I)*XTRA
              P(I)=TEMP
   15         SUM=SUM+TEMP
```

```
            ALFFAC=SUM                                                              FAC    59
            RETURN                                                                  FAC    60
      C                                                                             FAC    61
      16    RHOSTR=1.+RHOFAC*EXP(-H*(6.738E-5+9.61E-9*H))                           FAC    62
            AS=RHOSTR*EXP(-10.047+H*(-6.38HE-4+H*2.25E-8))                          FAC    63
            IF (H .GT. 8000) AS = EXP(-(((RH*.9471)* 10.37917)+((4.6303E-4-(RH      TCP    32
      1*1.6251E-4))*H)))                                                            TCP    33
            AS3 = AS                                                                TCP    34
            AS3 = ALFAS                                                             TCP    35
            TEMP=P(1)*EXP(-(AS+ALFAS)*DZ)                                           FAC    64
            P(1)=TEMP                                                               FAC    65
      C                                                                             FAC    66
      17    GO TO J1(17,1P)                                                         FAC    67
            SUM=SUM+AS*TEMP                                                         FAC    68
      18    GO TO 19                                                                FAC    69
      19    SUM=SUM+TEMP                                                            FAC    70
            AS=RHOSTR*EXP(-10.082+H*(-6.952E-4+H*1.55E-8))                          FAC    71
            IF (H .GT. 8000) AS = EXP (-(((RH*.9474)*12.6721)+((2.9317E-4-(RH*      TCP    36
      11.6251E-4))*H)))                                                             TCP    37
            AS4 = AS                                                                TCP    38
            AS4 = ALFAS                                                             TCP    39
            TEMP=P(2)*EXP(-(AS+ALFAS)*DZ)                                           FAC    72
            P(2)=TEMP                                                               FAC    73
      C                                                                             FAC    74
      20    GO TO J2(20,21)                                                         FAC    75
            SUM=SUM+AS*TEMP                                                         FAC    76
      21    GO TO 22                                                                FAC    77
      22    SUM=SUM+TEMP                                                            FAC    78
            AS=EXP(-9.94B+H*(-2.199E-4-H*1.96E-9))                                  FAC    79
            IF(H .GT. 8000) AS=EXP(-(((RH*1.813)*4.8547)+((8.7225E-4-(R) *2.266     TCP    40
      17E-4))*H)))                                                                  TCP    41
            AS2 = AS                                                                TCP    42
            AS2 = ALFAS                                                             TCP    43
            TEMP=P(3)*EXP(-(AS+ALFAS)*DZ)                                           FAC    60
            P(3)=TEMP                                                               FAC    81
      C                                                                             FAC    82
      23    GO TO J3(23,24)                                                         FAC    83
            ALFFAC=SUM+AS*TEMP                                                      FAC    84
            RETURN                                                                  FAC    85
      24    ALFFAC=SUM+TEMP                                                         FAC    86
            RETURN                                                                  FAC    87
      C                                                                             FAC    88
      C     ENTRY ALFKAS                                                            FAC    89
            IF (LAM.EQ.2) GO TO 25                                                  FAC    90
            TEMP=P(1)*EXP(-ALFAEX(H)*DZ)                                            FAC    91
            P(1)=TEMP                                                               FAC    92
            ALFFAC=TEMP                                                             FAC    93
            RETURN                                                                  FAC    94
      C                                                                             FAC    95
      25    ASSIGN 18 TO J1                                                         FAC    96
            ASSIGN 21 TO J2                                                         FAC    97
            ASSIGN 24 TO J3                                                         FAC    98
            ASSIGN 14 TO J4                                                         FAC    99
            GO TO 8                                                                 FAC    100
      C                                                                             FAC    101
            END                                                                     FAC    102
                                                                                    FAC    103
```

```
        FUNCTION ALFAB (H)
C
C   SINGLE LINE ABSORPTION COEFFICIENTS IN 1/M
C
        COMMON /ALF4/ LAM,RH
        COMMON /ALFCTA/ DUMMY(7),ARL,ARE
        HF=3.281*H
        CALL MEGAIR (HF,TR,PMB, ....)
        P=0.359*PMB/0.47802025...
        T=T0*5.0/9.0
        PW=6.9724E-10*RH*P*EXP(0.0546*...)
        GO TO (1,5,8,11), LAM
C
C   LAMDA IS 10.6
C
1       IF (H.GT.16000.01 GO TO 2
        ALFC02=7.94577416E-5-2.10062795E-9*H-3.57576007E-12*H*H+1.073F6914
       1E-15*H**3-1.69454494E-19*H**4+1.50364450F-23*H**5-7.16578722E-28*H
       2**6+1.61586924E-32*H**7-1.13662124E-37*H**8
        GO TO 4
C
2       IF (H.GT.55000.01 GO TO 3
        ALFC02=7.67462658E-+-1.89713935E-7*H+1.98650379E-11*H*H-1.14976017
       1E-15*H**3+4.04716134E-20*H**4-8.90401506E-25*H**5+1.19826061E-29*H
       2**6-9.03345645E-35*H**7+2.92529072E-40*H**8
        GO TO 4
C
3       ALFC02=1.0E-7*EXP(-1.74E-4*H+12.18)
C
4       ALFH20=4.32E-9*PW*(P+193.0*PW)
        ALFAB=ALFC02+ALFH20
        RETURN
C
C   LAMDA IS 3.8
C
5       ALFH20=5.4E-6*PW
        IF (P.GE.0.21 ALFH20=-5.923E-7+8.3633E-6*PW+3.1184E-8*PW*PW
C
        IF (H.GT.7500.01 GO TO 6
        ALFC02=1.844E-6*EXP(-2.272E-4*H)
        GO TO 7
C
6       ALFC02=4.25E-6*EXP(-3.36E-4*H)
7       ALFAB=ALFH20+ALFC02
        RETURN
C
C   LAMDA IS 5.0
C
8       IF (PW.GT.4.5E-4; GO TO 9
        AAA=1.9222
        BBR=1.4032
        GO TO 10
9       AAA=1.1425...
        BRR=-4.6052
10      ALFAB=(1.E-3)*EXP(AAA*ALOG(PW)+RBR)
```

```
C                                                                   AAB    59
C        INSERT EQUATIONS FCR OTHER WAVELENGTHS HERE               AAB    60
C                                                                   AA3    61
11       ALFZAB=ABL*EXP(-AB2*H)                                     AA7    62
         RETURN                                                     AAY    63
         END                                                        AA7    64
                                                                    AA4    65
```

60

```
FUNCTION ALFAEX    73/74    OPT=0    TRACE          FTN 4.0+P357      04/08/75  13.18.27.   PAGE   1

C        FUNCTION ALFAEX (M)                                         AEX    2
C                                                                    AEX    3
C        THIS ROUTINE CALCULATES THE EXTINCTION COEFFICIENT IN 1/M   AEX    4
C                                                                    AEX    5
         COMMON /ALE / LAM,UM                                        AEX    6
         COMMON /ALFDTA/ DUMMY(7),ARL,ABE,SCL,SCE                    AEX    7
C                                                                    AEX    8
         GO TO (1,2,3,10), LAM                                       AEX    9
C                                                                    AEX   10
C        LAMDA IS 10.6                                               AEX   11
C                                                                    AEX   12
1        ALFASO=1.0E-6*EXP(4.75*RM)                                  AEX   13
         GO TO 4                                                     AEX   14
C                                                                    AEX   15
C        LAMDA IS 3.8                                                AEX   16
C                                                                    AEX   17
2        ALFASO=3.6E-6*EXP(4.1256*RM)                                AEX   18
         GO TO 4                                                     AEX   19
C                                                                    AEX   20
C        INSERT EQUATIONS FOR OTHER WAVELENGTHS HERE                 AEX   21
C                                                                    AEX   22
C                                                                    AEX   23
C                                                                    AEX   24
C        LAMDA IS 5.0                                                AEX   25
3        ALFASO=3.E-6*EXP(4.2*RM)                                    AEX   26
C                                                                    AEX   27
C        THE REST OF THE FUNCTION IS INDEPENDENT OF LAMDA            AEX   28
C                                                                    AEX   29
4        IF (M.GT.13500.0) GO TO 7                                   AEX   30
         IF (M.GT.9500.0) GO TO 6                                    AEX   31
         IF (M.GT.5000.0) GO TO 5                                    AEX   32
         ALFAS=ALFASO*EXP(-M/1.2E+3)                                 AEX   33
         GO TO 9                                                     AEX   34
C                                                                    AEX   35
5        ALFAS=ALFASO*2.586*EXP(-M*1.031E-3)                         AEX   36
         GO TO 9                                                     AEX   37
C                                                                    AEX   38
6        ALFAS=ALFASO*1.25-4                                         AEX   39
         GO TO 9                                                     AEX   40
C                                                                    AEX   41
7        IF (M.GT.25000.0) GO TO 8                                   AEX   42
         ALFAS=ALFASO*(-3.251E-3+3.738E-7*M-9.6557E-12*M*M)          AEX   43
         GO TO 9                                                     AEX   44
C                                                                    AEX   45
8        ALFAS=ALFASO*1.8E-3*EXP(-1.535E-4*(M-25000.))               AEX   46
         ALFAS = ALFAS/9.7725                                        TCP   44
         ALFAEX=ALFAS*ALFAR(M)                                       AEX   47
         RETURN                                                      AEX   48
C                                                                    AEX   49
C        USER SPECIFIED COMPUTATION                                  AEX   50
10       ALFAEX=AEL*EXP(-ARL*M)+SCL*EXP(-SCE*M)                      AEX   51
         RETURN                                                      AEX   52
         END                                                         AEX   53
```

B-32

```
         FUNCTION CNSQ (H)
C
C        ATMOSPHERIC STRUCTURE CONSTANT IN M00(Z/3)
C        COMMON /CNVA/ IW
C
         IF (H.GE.1.0) GO TO 4
C        SET CNSQ FOR ALTITUDES LESS THAN 1 METER
C
         GO TO (1,2,3), IW
C        BAD WEATHER CONDITIONS
1        CNSQ=2.25E-13
         RETURN
C        NOMINAL WEATHER CONDITIONS
2        CNSQ=1.0E-13
         RETURN
C        GOOD WEATHER CONDITIONS
3        CNSQ=5.5E-15
         RETURN
C
C        CALCULATE CNSQ FOR ALTITUDES AT OR ABOVE 1 METER
C
4        GO TO (5,9,10), IW
C        BAD WEATHER CONDITIONS
5        IF (H.GT.100.0) GO TO 7
         IF (H.GT.10.0) GO TO 6
         CNSQ=2.9E-13*H**(-0.6993)
         RETURN
6        CNSQ=9.646E-13*H**(-1.216)
         RETURN
7        IF (H.GT.1.0E4) GO TO 8
         CNSQ=2.56E-12*H**(-1.6386)
         RETURN
8        IF (H.GT.1.5E4) GO TO 9
         CNSQ=2.0E-15
         RETURN
C        NOMINAL WEATHER CONDITIONS
9        CNSQ=2.0E-16
         IF (H.LE.11600..OR.H.GE.12600.) CNSQ=1E-13*H**(-1.07535)
         RETURN
C        GOOD WEATHER CONDITIONS
10       IF (H.GT.2.5E3) GO TO 12
         IF (H.GT.20.0) GO TO 11
         CNSQ=8.585E-15*H**(-0.6446)
         RETURN
11       CNSQ=1.51E-13*H**(-1.396)
```

FUNCTION CNSO   73/74   OPT=0   TRACE   FTN 4.0+P357   03/05/75   18.22.15.   PAGE   2

```
C
12      RETURN
        IF (H.GT.1425.1.0) GO TO 4
        CNSO=3.0E-12
        RETURN
        END
```

```
CN2     59
CO7     60
COC2    61
COC2    62
COC2    63
        64
```

```
      REAL FUNCTION KI(IBEAM,X)                                           2
C                                                                         3
C     COMPUTES THE INTENSITY RATIO                                        4
      IF (X.GT.0.0) GO TO 1                                               5
      KI=1.0                                                              6
      RETURN                                                              7
  1   X2=X*X                                                              8
      IF (IBEAM.EQ.0) GO TO 5                                             9
C                                                                        10
C     FOCUSED BEAM                                                       11
      X32=X**1.5                                                         12
      X15=X**2                                                           13
      IF (X.GT.1.0) GO TO 2                                              14
      KI=.174*X32+.144/X15+.733*EXP(-X2)                                 15
      RETURN                                                             16
  2   IF (X.GT.2.0) GO TO 3                                              17
      KI=-.174*X+.793                                                    18
      RETURN                                                             19
  3   IF (X.GT.100.0) GO TO 4                                            20
      X2=X2*X2*X                                                         21
      X36=X**.75                                                         22
      KI=-1.67/X36+6.3/X32+2.62/X36-12.9/(X2+1)-1.71*ALOG(X)/X           23
      RETURN                                                             24
  4   KI=EXP(-2.445*ALOG(X)+5.378)                                       25
      RETURN                                                             26
C                                                                        27
C     COLLIMATED BEAM                                                    28
  5   X4=X2*X2                                                           29
      IF (X.GE.5.0) GO TO 6                                              30
      X12=X**.5                                                          31
      X13=X**(1./3.)                                                     32
      X36=X**.75                                                         33
      KI=-4.14E-4*X4-2.99E-5/X4+.599*X13-.344/X12+.6*X/X36               34
      RETURN                                                             35
  6   KI=EXP(-2.183*ALOG(X)+3.145)                                       36
      RETURN                                                             37
      END                                                                38
```

```
      FUNCTION GALTIN (M)
C
C     ALTITUDE DEPENDENT PARAMETERS FOR THE BLOOMING CALCULATION--CHANGE
C     IN REFRACTIVE INDEX FOR A GIVEN TEMPERATURE CHANGE DIVIDED BY THE
C     REFRACTIVE INDEX,DENSITY,AND SPECIFIC HEAT.
C
      DIMENSION FAC(101)
      DATA FAC/-.772408,-.791416,-.813310,-.832184,-.854079,-.877086,-.9
     103245,-.926774,-.953647,-.982071,-1.012121,-1.043965,-1.044585,-1.
     2044545,-1.044604,-1.044614,-1.044619,-1.044624,-1.044633
     3,-1.044637,-1.039937,-1.034473,-1.030055,-1.025143,-1.020144,-1.01
     45573,-1.010434,-1.00613M,-1.001643,-.844875,-.992306,-.957714,-.97
     55543,-.963305,-.952747,-.940452,-.929444,-.917660,-.907560,-.894666
     62,-.884660,-.874466,-.866553,-.856454,-.847361,-.839069,-.829781,-
     7.825451,-.825451,-.825451,-.825451,-.829522,-.837476,-.84
     82554,-.847226,-.854941,-.862844,-.869920,-.876872,-.884877,-.84440
     94,-.905420,-.924922,-.940929,-.957644,-.974513,-.992244,-1.010461,
     S-1.024429,-1.043577,-1.204224,-1.235441,-1.243469,-1.263544,-1.154
     5.243544,-1.263549,-1.263549,-1.243549,-1.243549,-1.24356
     S9,-1.263458,-1.242521,-1.221822,-1.202361,-1.183508,-1.165296,-1.1
     S07517,-1.130327,-1.113643,-1.097663,-1.081111/
C
      IF (M.GE.1.E5) GO TO 1
      IM=M+1.E-3
      DM=(M-FLOAT(IM)*1.E3)*1.E-3
      I=IM+1
      IF (IM.LE.1) IM=2
      GALTIN=(FAC(IM)+(FAC(IM+1)-FAC(IM))*DM)*1.E-9
      RETURN
C
    1 GALTIN=FAC(101)*1.E-9
      RETURN
C
      END
```

```
C       SUBROUTINE MEGAIR (H,TM,PMB,O,G)
C
C       *******************************************************************
C       *       *       *       *       *       *       *       *       *
C       *   **  *  ** *  ****  *  ****  *  ****  *  ****  *  ****  *  ***  *
C       *  *  * * *  * * *     * *      * *      * *      * *   *  * *     *
C       * *   * * *  * * *     * *      * *      * *      * *   *  * *     *
C       * *   * * *  * * ****  * ****   * *      * ****   * ****   *  ***  *
C       * *   * * *  * * *     * *      * *      * *      * *  *   *     * *
C       *  *  * * *  * * *     * *      * *      * *      * *   *  *     * *
C       *   **  *  ** *  ****  *  ****  *  ****  *  ****  * *    * *  ***  *
C       *       *       *       *       *       *       *       *       *
C       *******************************************************************
C
C       MEGAIR2 CALCULATES ATMOSPHERE PARAMETERS (SPECIFICALLY
C       GEOPOTENTIAL HEIGHT, TEMPERATURE, PRESSURE, DENSITY,
C       GRAVITATIONAL ACCELERATION, AND THE SPEED OF SOUND) FROM
C       GEOMETRIC HEIGHT.
C       MEGAIR2 ACCEPTS HEIGHTS IN ANY ORDER AND WORKS EQUALLY WELL
C       WITH ORDERED OR RANDOM VALUES.
C       MEGAIR2 ACCEPTS VALUES OF H FROM -16500 FEET TO 320000 FEET.
C       ACCURACY OF VALUES WHEN H IS LESS THAN 300000 FEET IS BETTER
C       THAN .05 PERCENT.  ACCURACY OF VALUES WHEN H IS GREATER THAN
C       300000 FEET IS BETTER THAN .1 PERCENT.
C       MEGAIR2 IS BASED ON U.S. STANDARD ATMOSPHERE 1962.
C
C       DEFINE CONSTANTS
C
C       ENGLISH UNITS ARE USED THROUGHOUT MEGAIR2.
C       DLO = DENSITY AT SEA LEVEL  LB/FT**3
C       GAMMA = CONSTANT
C       GO = GRAVITATIONAL ACCELERATION AT SEA LEVEL  FT/SEC/SEC
C       MWO = MOLECULAR WEIGHT OF AIR AT SEA LEVEL  LB/LB MOL
C       PLC = SEA LEVEL PRESSURE  LB/FT**2
C       R = GAS CONSTANT  (LB FT)**2/(SEC**2(LB MOL)(DEGREE R))
C       RO = RADIUS OF EARTH  FEET
C
C       REAL L,MW,MWO
C
        DIMENSION DELTAM(22), DELTAT(22), DELTAP(22), DELTAL(22),
        DIMENSION COEFF1(22), COEFF2(22), COEFF3(22)
C
        DATA R,RO,GO,MWO/49719.,20851586.,369.,32.174049,28.9644/
C
C       DEFINE CONVERSION FACTORS
C       XMA CONVERTS LB/FT**2 TO MILLIBARS.
        DATA XMA/.47880257/
C
C       DEFINE LAYER BOUNDARY HEIGHTS AND THEIR ASSOCIATED TEMPERATURES,
C       PRESSURES, AND GRADIENTS.
        DATA (DELTAM(I),I=1,22)/0.,36152.,65827.,105518.,155348.,172011.,2
       102070.,262467.,295276.,328084.,360492.,393701.,492126.,524934.,557
       2743.,623300.,754453.,944252.,1012336.,1640420.,1968504.,2294588./
        DATA (DELTAT(I),I=1,22)/518.67,389.97,389.97,411.57,487.17,487.17,
       1454.77,325.17,325.17,379.17,469.17,649.17,1729.17,1899.17,2179.17,
       22231.17,2701.17,3295.17,3889.17,4357.17,4663.17,4461.17/
```

```
      DATA (DELTAB(I),I=1,22)/7.65738,6.1584186,6.7392202,2.4975073,.H3    MEG    59
     199754,.20664176,-.96673964,-3.8316924,-5.674314,-7.372763,-8.7411    MEG    60
     22522,-9.85154047,-11.4573394,-11.772702,-12.052080,-12.557150,-13.    MEG    61
     34413953,-14.74H3118,-16.2904,-17.5928,-18.74H40,-19.H1142/           MEG    62
      DATA (DELTAL(I),I=1,22)/-.0036416,0.,.00054844,.001536192,0.,-.00    MEG    63
     1109728,-.02219455,0.,-.00164592,.0027432,.0054864,.0109728,.00H2298    MEG    64
     2,.0054864,.96384048,.0027432,.00210456,.001810512,.001426464,.0009    MEG    65
     332688,.0003635504,.0003635504/                                        MEG    66
C                                                                           MEG    67
C     DEFINE MOLECULAR WEIGHT EQUATION COEFFICIENTS.                        MEG    68
      DATA (COEFF1(I),I=1,22)/0.,0.,0.,0.,0.,0.,20,74,32,15,33,90,          MEG    69
     141,98,30,64,30,H4,31,56,31,37,31,35,33,36,36,4973,34,8002,20,82470    MEG    70
     226,20,824706/                                                         MEG    71
      DATA (COEFF2(I),I=1,22)/0.,0.,0.,0.,0.,0.,0000259740,.6000            MEG    72
     10092126,.0C0014H,.0006542400,.00007964H75,.0000091666  MEG    73
     26,.00000H457143,.0000004H3333,.000012794H75,.0008178743,.0001H0446H    MEG    74
     38,.00000202009412,.000002029412/                                      MEG    75
      DATA (COEFF3(I),I=1,22)/0.,0.,0.,0.,0.,0.,0.,0.,0.,AE-11,0            MEG    76
     1.,0.,0.,0.,-1.9531125E-12,-4.0E-12,3.5156E-12,0.,0./                  MEG    77
C                                                                           MEG    78
C     MAKE AN INDEX APPROXIMATION USING A STRAIGHT LINE APPROXIMATION TO     MEG    79
C     GRAPH OF H VERSUS I.                                                   MEG    80
      IF (H.LT.-16500.) GO TO 9                                             MEG    81
      IF (H.GT.50000.) GO TO 5                                              MEG    82
      I=.0000257364H+1.88                                                   MEG    83
      IF (ABS(H).GE.DELTAH(I)) GO TO 1                                      MEG    84
      IF (ABS(H).GE.DELTAH(I-1)) I=I-1                                      MEG    85
C                                                                           MEG    86
C     ESTABLISH BASE VALUES OF PRESSURE, TEMPERATURE, AND GRADIENT.          MEG    87
    1 HI=DELTAH(I)                                                          MEG    88
      HPP=HI/(1.+H/RO)                                                      MEG    89
      TH=DELTAT(I)                                                          MEG    90
      PB=DELTAP(I)                                                          MEG    91
      L=DELTAL(I)                                                           MEG    92
C                                                                           MEG    93
C     PERFORM CALCULATIONS FOR H LESS THAN 300000 FEET.                      MEG    94
C                                                                           MEG    95
C     GEOPOTENTIAL HEIGHT                                                    MEG    96
      HP=H/(1.+H/RO)                                                        MEG    97
C                                                                           MEG    98
C     TEMPERATURE                                                            MEG    99
C     UP TO 300000 FEET, MOLECULAR SCALE TEMPERATURE EQUALS KINETIC          MEG   100
C     TEMPERATURE.                                                           MEG   101
      TM=TH+L*(HP-HPB)                                                      MEG   102
C                                                                           MEG   103
C     PRESSURE (P), IN LB/FT**2.                                            MEG   104
      IF (L) 2,3,2                                                          MEG   105
    2 P=EXP(PB-(GO*XMO/(L*R))*ALOG(TM/TB))                                  MEG   106
      GO TO 4                                                               MEG   107
    3 P=EXP(PB-(GO*XMO/R)*((HP-HPB)/TB))                                    MEG   108
    4 PM=P*XMR                                                              MEG   109
C                                                                           MEG   110
C     DENSITY                                                               MEG   111
      D=(XMO*P*GO)/(R*TM)                                                   MEG   112
C                                                                           MEG   113
C     GRAVITATIONAL ACCELERATION                                            MEG   114
                                                                            MEG   115
```

```
115        G=GO*(RO/(RO+H))**2                                              MEG  116
           RETURN                                                           MEG  117
C                                                                           MEG  118
C     PERFORM CALCULATIONS FOR H GREATER THAN 300000 FEET.                  MEG  119
C                                                                           MEG  120
C     SINCE MOLECULAR WEIGHT IS NO LONGER CONSTANT, MOLECULAR SCALE         MEG  121
C     TEMPERATURE IS NO LONGER EQUAL TO KINETIC TEMPERATURE.                MEG  122
C     THREE INDEX EQUATIONS ARE REQUIRED IN THE REGION ABOVE 300000 FEET    MEG  123
C     MAKE AN INDEX APPROXIMATION FOR VALUES OF H GREATER THAN 300000       MEG  124
C     FEET BUT LESS THAN 492126 FEET.                                       MEG  125
C                                                                           MEG  126
5    IF (H.GT.492126.) GO TO 7                                              MEG  127
     I=.00025734*H+1.R8                                                     MEG  128
     IF (I.GT.12) I=12                                                      MEG  129
     IF (H.GE.DELTAH(I)) GO TO 6                                            MEG  130
     IF (H.GE.DELTAH(I-1)) I=I-1                                            MEG  131
C                                                                           MEG  132
C     ESTABLISH BASE VALUES OF TEMPERATURE, PRESSURE, AND GRADIENT.         MEG  133
6    HB=DELTAH(I)                                                           MEG  134
     TB=DELTAT(I)                                                           MEG  135
     PB=DELTAP(I)                                                           MEG  136
     L=DELTAL(I)                                                            MEG  137
C                                                                           MEG  138
C     CALCULATE MOLECULAR WEIGHTS FROM EMPIRICAL, GRAPHICALLY DERIVED.      MEG  139
C     EQUATIONS.                                                            MEG  140
     MH=COEFF1(I)+COEFF2(I)*H+COEFF3(I)*H*H                                 MEG  141
     HP=H/(1.+H/RO)                                                         MEG  142
C                                                                           MEG  143
C     CALCULATE MOLECULAR SCALE TEMPERATURE AND CONVERT TO KINETIC          MEG  144
C     TEMPERATURE.                                                          MEG  145
     TM=((TB+L*(H-HB))*MH)/MWO                                              MEG  146
C                                                                           MEG  147
C     PRESSURE (P), IN LB/FT**2.                                            MEG  148
     X=RO+HB-TB/L                                                           MEG  149
     Y=1./(X*(RO+H))-1./(X*(RO+HB))+(1./(X*X))*ALOG(((H-HB+TB/L)*(RO+HB))   MEG  150
    1)*L)/((RO+H)*(H))                                                      MEG  151
     B=(GO*MWO*RO*RO)/(L*R)                                                 MEG  152
     P=EXP(PB-B*Y)                                                          MEG  153
     PHR=P*XHB                                                              MEG  154
C                                                                           MEG  155
C     DENSITY                                                               MEG  156
     D=(MW*P*GO)/(R*TM)                                                     MEG  157
C                                                                           MEG  158
C     GRAVITATIONAL ACCELERATION                                           MEG  159
     G=GO*(RO/(RO+H))**2                                                    MEG  160
     RETURN                                                                 MEG  161
C                                                                           MEG  162
C     MAKE AN INDEX APPROXIMATION FOR VALUES OF H GREATER THAN 492126       MEG  163
C     FEET BUT LESS THAN 984252 FEET.                                       MEG  164
C                                                                           MEG  165
7    IF (H.GT.984252.) GO TO 8                                              MEG  166
     Z=(H-749000.)/50000.                                                   MEG  167
     I=17.5+.5648*Z-.04348*Z*Z                                             MEG  168
     IF (H.GE.DELTAH(I)) GO TO 6                                            MEG  169
     IF (H.GE.DELTAH(I-1)) I=I-1                                            MEG  170
     GO TO 6                                                                MEG  171
C                                                                           MEG  172
```

```
        C     MAKE AN INDEX APPROXIMATION FOR VALUES OF H GREATER THAN 984252          MEG   173
        C     FEET.                                                                    MEG   174
        C                                                                              MEG   175
  175   8     IF (H.GT.2320000.) GO TO 9                                               MEG   176
              I=.00003048*H+15.                                                        MEG   177
              IF (H.GE.DELTAH(I)) GO TO 6                                              MEG   178
              IF (H.GE.DELTAH(I-1)) I=I-1                                              MEG   179
              GO TO 6                                                                  MEG   180
        C                                                                              MEG   181
  180   9     WRITE (6,10) H                                                           MEG   182
              RETURN                                                                   MEG   183
        C                                                                              MEG   184
        C                                                                              MEG   185
  185   10    FORMAT (1H ,20X,22H**ERROR FROM MEGAIR2**,5H H = ,E12.5)                 MEG   186
              END                                                                      MEG   187
                                                                                       MEG   188
```

```
          FUNCTION VX (GL,H,HOM,PHI,ZJ)
C
C     CROSS WIND VELOCITY PLUS SLEW VELOCITY IN METERS/SECOND
C
          COMMON /MESH/ XTRA,ZPREV
          COMMON /CNVW/ IW
          COMMON /X/ CHI,OMEGA,VP,VPSC,VXB
C
          VX=VXB
          IF (VXB.NE.0.) RETURN
C
          VS=OMEGA*(ZJ-ZPREV)
          VX=13.6
          IF (H.GE.5.E4) GO TO 6
          IF (H.GE.2.44E4) GO TO 2
          IF (H.GE.1.22E4) GO TO 1
          VX=3.42E-3*H+8.75
          GO TO 3
  1       VX=R2.4-2.53E-3*H
          GO TO 3
  2       VX=27.2-2.72E-4*H
  3       IF (IW-2) 4,5,6
  4       VX=VX*0.27
          GO TO 6
  5       VX=VX*0.5
  6       IF ((HOM-GL).GT.10.) VX=VX*0.2
          IF (VPSC.GE.VX) VX=VPSC
          VX=VX+VS
          RETURN
          END
```

SHORT OUTPUT FORMAT, WITHOUT DEBUG

TARGET RANGE (L) ----------------- 1.000E-03 METERS   DEVICE POWER (PD) ------------ 1.000E+06 WATTS
FOCAL DISTANCE (FL) -------------- 1.000E+03 METERS   POWER OUT OF THE TELESCOPE (PT) --- 0. WATTS

GROUND LEVEL (GL) ---------------- 0. METERS   WAVELENGTH (LAM_A) ------------- 3.80E-06 METERS
DEVICE ALTITUDE (HOM) ------------ 1.00E+02 METERS   INPUT JITTER (GH FREQUENCY) --- 5.00E-06
                 3.28E+02 FEET   (LOW FREQUENCY) --- 5.00E-06
TARGET ALTITUDE (HTM) ------------ 0. METERS   TRACKING RATE (OMEG --------- 0.00 RADIANS/SEC
                 0. FEET   OPTICS RADIUS (RO) ----------- .35 METERS
VERTICAL ANGLE (PHI) ------------- -.000 RADIANS   OBSCURATION RADIUS ----------- .06 METERS

AZIMUTH ANGLE (CHI) -------------- .520 RADIANS   BEAM TYPE (PROP) -------------- GAUSSIAN
PLATFORM VELOCITY (VP) ----------- 0.METERS/SEC   TYPE OF PROPAGATION (BEAM) ---- FOCUSED
SPECIFIED CROSS WIND (VXB) ------- 10.00   BEAM QUALITY (M) -------------- 1.50
SEVERITY OF TURBULENCE (WTHR) ---- NORMAL   NUMBER OF BEAMPATH INCREMENTS - 36
RELATIVE HUMIDITY (RH) ----------- .50

•••••••••••••••••••••••••••••••INPUT TO OPTICAL TRAIN•••••••••••••••••••••••••••••••

LASER BEAM DIAMETER   .1600 METERS
LASER POWER   .1000E+07 WATTS
WAVELENGTH   .3800E-05 METERS
OBSCURATION   .3600
BEAM QUALITY   1.500
PULSE LENGTH   2.000 SECONDS
PHASE FRONT CURVATURE   .1000E+71 METERS
JITTER   .7071E-05 RADIANS
INTENSITY FLUCTUATIONS   .5000 PEAK-TO-PEAK
SCALE SIZE OF FLUCTUATIONS   .1000 L/AT
TYPE OF AEROWINDOW   FOCUSED
AERODYNAMIC DELTA RHO/RHO   .1000
RHO/RHO REF   2.500
DISTANCE TO CLIPPER   50.00 METERS
CLIPPER DIAMETER   .1600 METERS
NUMBER OF MIRRORS   7
REFLECTIVITY   .9460
FABRICATION ERROR   .1250 VIS. LAMBDAS
TYPE OF MIRRORS   COOLED
DISTANCE BETWEEN MIRRORS   .1500 METERS
TELESCOPE MAGNIFICATION   4.375
TELESCOPE DIAMETER   .7000 METERS
TELESCOPE TYPE   ON-AXIS
TYPE OF EXIT APERTURE   WINDOW
EXIT APERTURE LENGTH   .5000E-01 METERS
ABSORPTION COEFFICIENT   .1000E-01 METERS-1
TEMPERATURE FLUCTUATION   1.000 DEG K
STRUT AREA/ BEAM AREA   .5000E-01
TRACKER JITTER   .5000E-05 RADIANS
BORE-SIGHT JITTER   .5000E-05 RADIANS
SERVO JITTER   .5000E-05 RADIANS
AUTOALIGNMENT JITTER   .5000E-05 RADIANS

••••••••••••••••••••••••••••OPTICAL TRAIN OUTPUT••••••••••••••••••••••••••••••••

SOURCE		TRANSMISSION	SIGMA	L/WT
INPUT BEAM		1.0000	.3333	0.0000
AERODYNAMIC WINDOW		1.0000	0.0000	0.0000
BEAM CLIPPER		1.0000	0.0000	0.0000
MIRRORS	COOLED	.9060	.3028	.0007
BEAM EXPANDER	ON-AXIS	.9570	.3418	.5951
EXIT APERTURE	WINDOW	.9495	.0593	.1000
TOTALS		.8233	.8977	.1673

TRANSMITTED BEAM DIAMETER .7000 METERS
TRANSMITTED POWER .4633E+05 WATTS
BEAM QUALITY BEFORE ACCOUNTING FOR DIVERGENCE
M1 = .4937   M2 = 1.1130

EFFECT OF BEAM DIVERGENCE ON WAIST   1.000
FINAL BEAM SPREAD PARAMETER. M2   1.113
TOTAL BEAM JITTER .4984E-05 RADIANS
PHASE FRONT CURVATURE .4375E+71 METERS

RESULTANT BEAM QUALITY   M1 = .560   M2 = 1.215

CALCULATIONS FOR ORIGIN BELOW 100 KM AND TARGET BELOW 100 KM.

TARGET ALTITUDE (HTH) = 0.   METERS (0.   FEET)
TARGET RANGE (L) = 1.005E+03 METERS
LINEAR EFFECTS ON TRANSMISSION (EXPKAS) = .946
NON-LINEAR EFFECTS ON TRANSMISSION (KIP) = .500
AREA WITHOUT BLOOMING (APEA) = 1.065E-03 METERS**2
AREA WITH BLOOMING (BLAREA) = 2.131E-03 METERS**2

LONG-TERM TURBULENCE (SIGMAT)	= 1.159E-06	RADIANS
SHORT-TERM TURBULENCE (SIGTST)	= 8.633E-07	RADIANS
RADIUS WITHOUT BLOOMING (R)	= .018	METERS
AVERAGE INTENSITY (I?)	= 1.7712E-08	WATTS/M**2
PEAK INTENSITY (IP)	= 4.0958E-08	WATTS/M**2

DISPLACEMENT = .025 METERS   ECCENTRICITY = .650

I/IPEAK CONTOUR	AREA (METER**2)	CUMULATIVE POWER	AVERAGE INTENSITY
.9	1.122E-04	3.774E+04	3.262E+08
.8	2.377E-04	7.547E+04	3.175E+08
.7	3.806E-04	1.126E+05	2.979E+08
.6	5.442E-04	1.509E+05	2.774E+08
.5	7.384E-04	1.887E+05	2.555E+08
.4	9.761E-04	2.264E+05	2.326E+08
.3	1.263E-03	2.642E+05	2.090E+08
.2	1.715E-03	3.019E+05	1.761E+08
.1	2.453E-03	3.396E+05	1.385E+08

POWER RANGE AVAILABLE

TELESCOPE POWER (WATTS)	INTENSITY (WATTS/M**2)	USEFUL POWER (WATTS)	OVER AREA (M**2)
8.233E-04	3.426E-07	3.542E-07	1.139E-02
1.647E-05	6.383E-07	7.085E-07	1.307E-02
2.470E-05	8.607E-07	1.063E-08	1.469E-02
3.293E-05	1.063E-04	1.417E-08	1.652E-02
4.116E-05	1.199E-04	1.771E-08	1.853E-02
4.940E-05	1.311E-08	2.124E-08	2.051E-02
5.763E-05	1.454E-08	2.478E-08	2.175E-02
6.526E-05	1.573E-08	2.765E-08	2.307E-02
7.409E-05	1.647E-04	3.196E-08	2.450E-02
8.233E-05	1.771E-04	3.543E-08	2.605E-02
9.056E-05	1.834E-04	3.867E-08	2.777E-02
9.879E-05	1.374E-08	4.251E-08	2.957E-02
1.070E-05	1.935E-04	4.605E-08	3.128E-02
1.153E-06	1.975E-04	4.960E-08	3.270E-02
1.235E-06	2.062E-04	5.314E-08	3.405E-02
1.317E-06	2.127E-04	5.669E-08	3.534E-02
1.400E-06	2.184E-04	6.023E-08	3.652E-02
1.482E-05	2.239E-04	6.377E-08	3.791E-02
1.564E-05	2.240E-04	6.731E-08	3.922E-02
1.647E-05	2.335E-04	7.085E-08	4.055E-02

USEFUL INTENSITY = 1.020E-06 WATTS/M**2

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